

## CRITICAL THINKING

1. Explain why you agree or disagree with the proposals made by health officials for reducing the death toll and other harmful effects of smoking listed on p. 396.
2. Do you think chemicals should be regulated based on their effects on the nervous, immune, and endocrine systems? Explain.
3. Should we have zero pollution levels for all hazardous chemicals? Explain.
4. Do you believe that health and safety standards in the workplace should be strengthened and enforced more vigorously, even if this causes a loss of jobs when companies transfer operations to countries with weaker standards? Explain.
5. Evaluate the following statements:
  - a. We should not get so worked up about exposure to toxic chemicals because almost any chemical can cause some harm at a large enough dosage.
  - b. We should not worry so much about exposure to toxic chemicals because through genetic adaptation we can develop immunity to such chemicals.
  - c. We should not worry so much about exposure to toxic chemicals because we can use genetic engineering to reduce or eliminate such problems.
6. How can changes in the age structure of a human population increase the spread of infectious diseases? How can the spread of infectious diseases affect the age structure of human populations?
7. Should pollution levels be set to protect the most sensitive people in a population (Figure 16-3, left) or the average person (Figure 16-3, middle)? Explain.
8. What are the five major risks you face from your lifestyle, where you live, and what you do for a living? Which of these risks are voluntary and which are involuntary? List the five most important things you can do to reduce these risks. Which of these things do you actually plan to do?
9. How would you answer each of the questions raised about (a) risk analysis on p. 412, and (b) risk assessment and risk management on p. 413? Explain each of your answers.

## PROJECTS

1. Assume that members of your class (or small manageable groups in your class) have been appointed to a technology risk-benefit assessment board. As a group, decide why you would approve or disapprove of widespread use of each of the following: (a) drugs to retard aging, (b) electrical or chemical devices that would stimulate the brain to eliminate anxiety, fear, unhappiness, and aggression, and (c) genetic engineering to produce people with superior intelligence and strength.
2. Use the library or the internet to find recent articles describing the rise of genetic resistance of disease-causing bacteria to commonly used antibiotics. Evaluate the evidence and claims in these articles.

3. Pick a specific viral disease and use the library or internet to find out about (a) how it spreads, (b) its effects, (c) strategies for controlling its spread, and (d) possible treatments.
4. Use the library or the internet to find bibliographic information about *Paracelsus* and *Joel Hirschorn*, whose quotes appear at the beginning and end of this chapter.
5. Make a concept map of this chapter's major ideas, using the section heads and subheads and the key terms (in boldface). Look at the inside back cover and on the website for this book for information about making concept maps.

## INTERNET STUDY RESOURCES AND RESOURCES FOR FURTHER READING AND RESEARCH



The website for this book contains helpful study aids and many ideas for further reading and research. Log on to:

<http://www.brookscole.com/product/0534376975s>

and click on the Chapter-by-Chapter area. Choose Chapter 16 and select a resource:

- "Flash Cards" allows you to test your mastery of the Terms and Concepts to Remember for this chapter.
- "Tutorial Quizzes" provides a multiple-choice practice quiz.
- "Student Guide to InfoTrac" will lead you to Critical Thinking Projects that use InfoTrac College Edition as a research tool.
- "References" lists the major books and articles consulted in writing this chapter.
- "Hypercontents" takes you to an extensive list of sites with news, research, and images related to individual sections of the chapter.

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Try the following articles:

Gregory, R. 2000. Using stakeholder values to make smarter environmental decisions. *Environment* vol. 42, no. 5, pp. 34–41. (subject guide: risk assessment)

Hunter, B.T. 2000. New alternatives in safety testing: testing product safety without using animals. *Consumers' Research Magazine* vol. 83, no. 5, pp. 26–30. (toxicology, technique)

# 17 AIR AND AIR POLLUTION

## When Is a Lichen Like a Canary?

Nineteenth-century coal miners took canaries with them into the mines—not for their songs, but for the moment when they stopped singing. Then the miners knew it was time to get out of the mine because the air contained methane, which could ignite and explode.

Today we use sophisticated equipment to monitor air quality, but living things such as lichens (Figure 17-1) still can warn us of bad air. A lichen consists of a fungus and an alga living together, usually in a mutually beneficial (mutualistic) partnership.

These hearty pioneer species are good air pollution detectors because they are always absorbing air as a source of nourishment. Certain lichen species are sensitive to specific air-polluting chemicals. Old man's beard (*Usnea trichodea*) (Figure 17-1, right) and yellow *Evernia* lichens, for example, sicken or die in the presence of too much sulfur dioxide.

Because lichens are widespread, long-lived, and anchored in place, they can also help track pollution to its source. The scientist who discovered sulfur dioxide pollution on Isle Royale in Lake Superior (Case Study, p. 204), where no car or smokestack had ever intruded, used *Evernia* lichens to point the finger northward to coal-burning facilities at Thunder Bay, Canada.

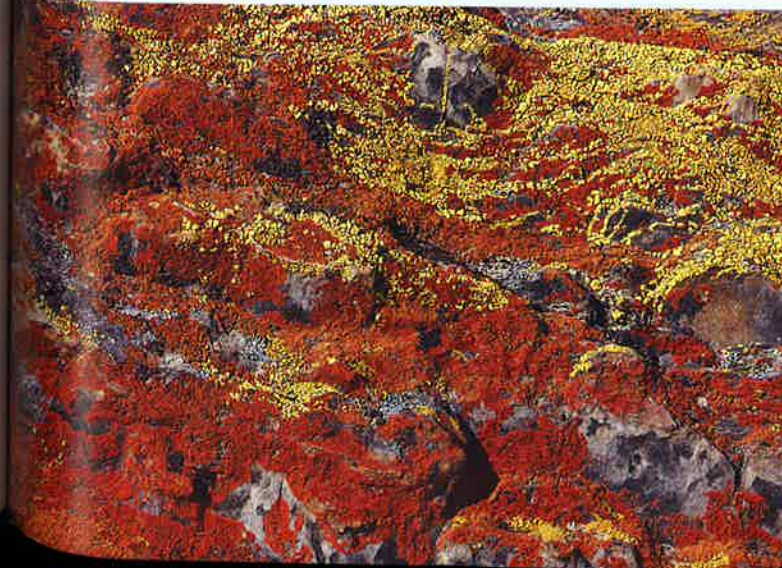
Radioactive particles spewed into the atmosphere by the Chernobyl nuclear power-plant disaster (p. 350) fell to the ground over much of northern Scandinavia

and were absorbed by lichens that carpet much of Lapland. The area's Saami people depend on reindeer meat for food, and the reindeer feed on lichens. After Chernobyl more than 70,000 reindeer had to be killed and the meat discarded because it was too radioactive to eat. Scientists helped the Saami identify which of the remaining reindeer to move by analyzing lichens (which absorbed some of the radioactive fallout) to pinpoint the most contaminated areas.

Last but not least, lichens can replace electronic monitoring stations that cost more than \$100,000 each. This is not so much a triumph of nature over technology as a partnership between the two, for technicians use highly sophisticated methods to analyze lichens for pollution and measure their rates of photosynthesis.

We all must breathe air from a global atmospheric commons in which air currents and winds can transport some pollutants long distances. Thus, air pollution anywhere is a potential threat elsewhere. Lichens can alert us to the danger, but as with all forms of pollution, the best solution is prevention.

**Figure 17-1** Red and yellow crustose lichens growing on slate rock in the foothills of the Sierra Nevada near Merced, California (left), and *Usnea trichodea* lichen growing on a branch of a larch tree in Gifford Pinchot National Park, Washington (right). The vulnerability of various lichen species to specific air pollutants can help researchers detect levels of these pollutants and track down their sources. (Left, Kenneth W. Fink/Ardea, London; right, Milton Rand/Tom Stack & Associates)





*I thought I saw a blue jay this morning. But the smog was so bad that it turned out to be a cardinal holding its breath.*

MICHAEL J. COHEN

This chapter addresses the following questions:

- What layers are found in the atmosphere?
- What are the major outdoor air pollutants, and where do they come from?
- What are two types of smog?
- What is acid deposition, and how can it be reduced?
- What are the harmful effects of air pollutants?
- How can we prevent and control air pollution?

## 17-1 THE ATMOSPHERE

**What Is the Troposphere? Weather Breeder** We live at the bottom of a sea of air called the **atmosphere**. This sea of life-sustaining gases surrounding the earth is divided into several spherical layers (Figure 17-2). Each layer is characterized by abrupt changes in temperature, the result of differences in the absorption of incoming solar energy.

About 75–80% of the mass of the earth's air is found in the atmosphere's innermost layer, the **troposphere**, which extends only about 17 kilometers (11 miles) above sea level at the equator and about 8 kilometers (5 miles) over the poles. If the earth were the size of an apple, this lower layer containing the air we breathe would be no thicker than the apple's skin. This thin and turbulent layer of rising and falling air currents and winds is the planet's weather breeder.

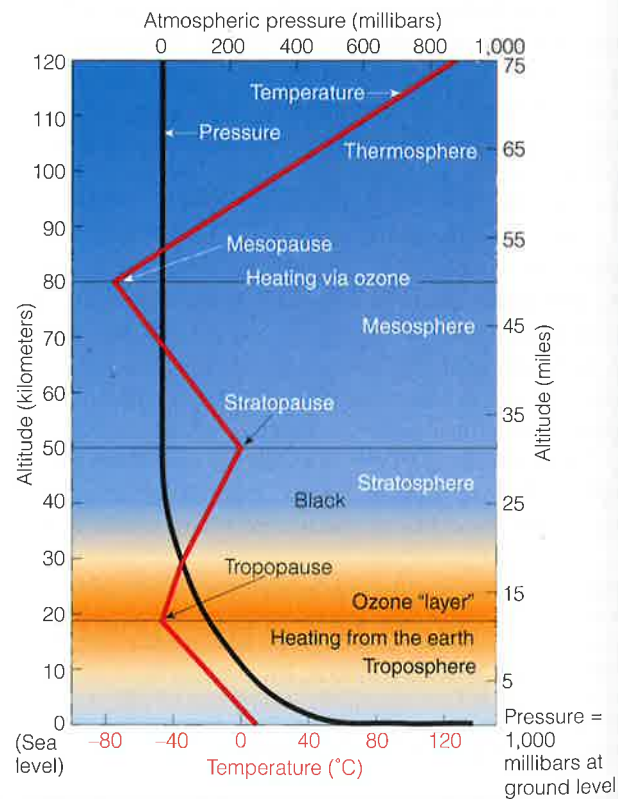
Take a deep breath. About 99% of the volume of the air you inhaled consisted of two gases: nitrogen (78%) and oxygen (21%). The remainder consisted of (1) water vapor (varying from 0.01% at the frigid poles to 4% in the humid tropics), (2) slightly less than 1% argon (Ar), (3) 0.037% carbon dioxide ( $\text{CO}_2$ ), and (4) trace amounts of several other gases.

During several billion years of chemical and biological evolution, the composition of the earth's atmosphere has varied (Spotlight, p. 106). A turning point occurred about 2.3–2.7 billion years ago when photosynthesizing cyanobacteria began adding oxygen to the troposphere.

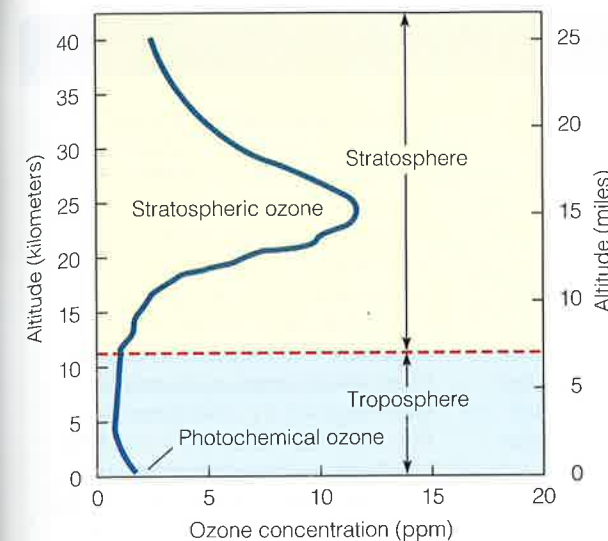
The fact that oxygen now makes up about 21% of the volume of the earth's atmosphere is fortunate for us and other species that survive by aerobic respiration (p. 80). Flammability calculations indicate that if oxygen levels were to rise above 25%, the earth would be an inferno. Essentially all vegetation and other organic material would burn. If levels were to fall below 15%, even the driest material would not burn.

Both the average pressure exerted by the gases in the atmosphere and their average density (mass of gases per unit volume) decrease with altitude. Temperature also declines with altitude in the troposphere but abruptly begins to rise at the top of this zone, called the **tropopause** (Figure 17-2). This temperature change limits mixing between the troposphere and upper layers of the atmosphere.

**What Is the Stratosphere? Earth's Global Sunscreen** The atmosphere's second layer is the **stratosphere**, which extends from about 17 to 48 kilometers (11 to 30 miles) above the earth's surface (Figure 17-2). Although the stratosphere contains less matter than the troposphere, its composition is similar, with two notable exceptions: (1) Its volume of water vapor is about 1/1,000 as much, and (2) its concentration of ozone is much higher (Figure 17-3).



**Figure 17-2** The earth's current atmosphere consists of several layers. The average temperature of atmosphere varies with altitude (red line). The average temperature of the atmosphere at the earth's surface is determined by a combination of (1) *natural heating* by incoming sunlight and certain greenhouse gases that release absorbed energy as heat into the lower troposphere (the *natural greenhouse effect*, Figure 6-13, p. 128) and (2) *natural cooling* by surface evaporation of water and convection processes that transfer heat to higher altitudes and latitudes (Figure 6-7, p. 125, and Figure 6-8, p. 126). Most UV radiation from the sun is absorbed by ozone ( $\text{O}_3$ ), which is found primarily in the stratosphere in the *ozone layer* between 17 and 26 kilometers (10 to 16 miles) above sea level.



**Figure 17-3** Average distribution and concentrations of ozone in the troposphere and stratosphere. *Beneficial ozone* that forms in the stratosphere protects life on earth by filtering out of the incoming harmful ultraviolet radiation emitted by the sun. *Harmful or photochemical ozone* forms in the troposphere when various air pollutants undergo chemical reactions under the influence of sunlight. Ozone in this portion of the atmosphere near the earth's surface damages plants, lung tissues, and some materials such as rubber. (Data from NOAA)

Stratospheric ozone is produced when some of the oxygen molecules there interact with ultraviolet (UV) radiation emitted by the sun. This "global sunscreen" of ozone in the stratosphere keeps about 95% of the sun's harmful UV radiation from reaching the earth's surface. This UV filter (1) allows humans and other forms of life to exist on land, (2) helps protect humans from sunburn, skin and eye cancer, cataracts, and damage to the immune system, and (3) prevents much of the oxygen in the troposphere from being converted to photochemical ozone, a harmful air pollutant (Figure 17-3).

Thus, certain levels of *stratospheric ozone* are essential to the continued existence of most life on the earth. On the other hand, very low levels of *tropospheric* or *photochemical ozone* damage plants and materials such as rubber and have harmful effects on our respiratory systems (Figure 17-3). There is much evidence that some human activities are (1) *decreasing* the amount of ozone in the stratosphere and (2) *increasing* the amount of ozone in the troposphere.

**What Are Two Important Global Processes Taking Place in the Atmosphere?** Two *natural processes* that play crucial roles in the earth's climate and biodiversity are the (1) *greenhouse effect* (Figure 6-13, p. 128), which helps heat the troposphere and the earth's surface, and (2) *ozone shield* in the stratosphere (Figure 17-2), which filters out most of the sun's UV radiation. Both of these natural processes are necessary for life as we

know it. However, there is much evidence that chemicals we add to the atmosphere can (1) enhance the natural greenhouse effect and lead to *global warming* (Section 18-2, p. 450) and (2) reduce the concentration of ozone in the stratosphere, an effect called *ozone depletion*, as discussed in Section 18-6 (p. 465).

**How Are We Disrupting the Earth's Gaseous Biogeochemical Cycles?** The earth's biogeochemical cycles (Section 4-6, p. 87) work well as long as we do not disrupt them by (1) overloading them with essential chemicals at certain points or (2) removing too many vital chemicals at other points. There is ample evidence that our activities are disrupting the

- *Carbon cycle* (Figure 4-29, p. 92) by adding about one-fourth as much  $\text{CO}_2$  to the troposphere (mostly from burning fossil fuels and clearing forests faster than they grow back) as the rest of nature. These human inputs of  $\text{CO}_2$  have the potential to warm the earth's atmosphere and alter global climate and food-producing regions (Sections 18-3 and 18-4).

- *Nitrogen cycle* (Figure 4-30, p. 94) by releasing three times more nitrogen oxides ( $\text{NO}$ ,  $\text{NO}_2$ , and  $\text{N}_2\text{O}$ ) and gaseous ammonia ( $\text{NH}_3$ ) into the troposphere (mostly from burning fossil fuels and using nitrogen fertilizers) than do natural processes. Most of the nitrogen oxides emitted into the troposphere are converted to nitric acid vapor ( $\text{HNO}_3$ ) and acid-forming nitrate salts. When these compounds dissolve in water and return to the earth's surface, they increase the acidity (Figure 3-7, p. 56) of soils, streams, and lakes and can harm plant and animal life.

- *Sulfur cycle* (Figure 4-33, p. 97) by releasing about twice as much sulfur dioxide ( $\text{SO}_2$ ) into the troposphere (mostly from petroleum refining and burning of coal and oil) as do natural sources. Much of this sulfur dioxide is converted to sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and sulfate salts that return to the earth's surface and increase the acidity of soils, streams, and lakes and harm plant and animal life.

- Biogeochemical cycles of toxic metals such as *arsenic*, *cadmium*, and *lead* by injecting into the troposphere about twice as much arsenic as the rest of nature, 7 times as much cadmium, and 27 times as much lead.

## 17-2 OUTDOOR AIR POLLUTION

**What Are the Major Types and Sources of Air Pollution?** Air pollution is the presence of one or more chemicals in the atmosphere in sufficient quantities and duration to cause harm to humans, other forms of life, and materials. The effects of airborne pollutants range from annoying to lethal. Air pollution is not new (Spotlight, p. 420).





## Air Pollution in the Past: The Bad Old Days

### SPOTLIGHT

Modern civilization did not invent air pollution. It probably began when humans discovered fire and used it to burn wood in poorly ventilated caves.

In A.D. 61, the Roman author Seneca wrote of the “stink, soot, and heavy air” from the burning of wood. During the Middle Ages a haze of wood smoke hung over densely packed urban areas.

The industrial revolution brought even worse air pollution as coal was burned to power factories and heat homes. In 1273, King Edward I of England banned the burning of coal in London (except by blacksmiths) to reduce air pollution. However, the ban was ignored because of a scarcity of fuelwood. More than 500 years later, the English poet Shelley observed, “Hell must be much like London, a smoky and populous city.”

By the 1850s, London had become well known for its “pea-soup” fog, consisting of a mixture of coal smoke and fog that blanketed the city. In 1880, a prolonged coal fog killed an estimated 2,200 people. Another in 1911 killed more than 1,100 Londoners. The authors of a report on this disaster coined the word *smog* for the deadly mixture of smoke and fog that enveloped the city.

In 1952, an even worse yellow fog lasted for 5 days and killed 4,000 Londoners, prompting Parliament to pass the Clean Air Act of 1956. Additional air pollution disasters in 1956, 1957, and 1962 killed 2,500 more people. Because of

strong air pollution laws, London’s air today is much cleaner, and “pea soup” fogs are a thing of the past.

The industrial revolution, powered by coal-burning factories and homes, brought air pollution to the United States. Large industrial cities such as Pittsburgh, Pennsylvania, and St. Louis, Missouri, were known for their smoky air. By the 1940s, the air over some cities was so polluted that people had to use their automobile headlights during the day.

The first documented air pollution disaster in the United States occurred during October 1948, at the town of Donora in Pennsylvania’s Monongahela River Valley south of Pittsburgh. Pollutants from the area’s industries became trapped in a fog that stagnated over the valley for 5 days. After several days the fog was so dense that people could not see well enough to drive, even at noon with their headlights on. About 7,000 of the town’s 14,000 inhabitants became sick, and 22 of them died. This killer fog resulted from a combination of mountainous terrain surrounding the valley and weather conditions that trapped and concentrated deadly pollutants emitted by the community’s steel mill, zinc smelter, and sulfuric acid plant.

In 1963, high concentrations of air pollutants accumulated in the air over New York City, killing about 300 people and injuring thousands. Other episodes in New York, Los Angeles, and other large cities in the 1960s led to much stronger air-pollution control programs in the 1970s.

Congress passed the original version of the Clean Air Act in

1963, but it did not have much effect until a stronger version of this law was enacted in 1970. The Clean Air Act of 1970 empowered the federal government to set air pollution emission standards (with an adequate safety margin) for automobiles and industries that each state was required to enforce. Even stricter emission standards were imposed by amendments to the Clean Air Act in 1977 and 1990.

Mostly as a result of these laws and actions by states and local areas, the United States has not had any more Donora or New York City incidents. The *good news* is that in most places smog has decreased and rain has become less acidic. Despite significant population growth and economic growth, emissions of the six most common (criteria) outdoor air pollutants decreased by 31% between 1970 and 1998.

However, the *bad news* is that much more can be done to continue improving air quality in the United States. According to the EPA, (1) about 62 million Americans are exposed to levels of one or more of the six most common outdoor air pollutants that exceed federal emission standards, and (2) air pollution in the United States causes the premature deaths of 150,000–350,000 people per year (most from exposure to indoor air pollution).

### Critical Thinking

Explain why you agree or disagree with the statement that air pollution in the United States should not be a major concern because of the significant progress in reducing outdoor air pollution since 1970.

volcanoes, (3) carbon oxides, nitrogen oxides, and particulates from forest fires, (4) hydrocarbons and pollen from live plants, (5) methane and hydrogen sulfide from decaying plants, and (6) salt particulates from the sea. Most natural sources of air pollution are spread out and, except for those from volcanic eruptions and some forest fires, rarely reach harmful levels.

Table 17-1 lists the major classes of pollutants commonly found in outdoor (ambient) air. Such air pollutants come from both natural sources and human (anthropogenic) activities. Examples of natural sources include (1) dust and other forms of suspended particulate matter from wind storms and soil (Figure 6-1, p. 120), (2) sulfur oxides and particulate matter from

Table 17-1 Major Classes of Air Pollutants

Class	Examples
Carbon oxides	Carbon monoxide (CO) and carbon dioxide (CO <sub>2</sub> )
Sulfur oxides	Sulfur dioxide (SO <sub>2</sub> ) and sulfur trioxide (SO <sub>3</sub> )
Nitrogen oxides	Nitric oxide (NO), nitrogen dioxide (NO <sub>2</sub> ), nitrous oxide (N <sub>2</sub> O) (NO and NO <sub>2</sub> often are lumped together and labeled NO <sub>x</sub> )
Volatile organic compounds (VOCs)	Methane (CH <sub>4</sub> ), propane (C <sub>3</sub> H <sub>8</sub> ), chlorofluorocarbons (CFCs)
Suspended particulate matter (SPM)	Solid particles (dust, soot, asbestos, lead, nitrate, and sulfate salts), liquid droplets (sulfuric acid, PCBs, dioxins, and pesticides)
Photochemical oxidants	Ozone (O <sub>3</sub> ), peroxyacyl nitrates (PANs), hydrogen peroxide (H <sub>2</sub> O <sub>2</sub> ), aldehydes
Radioactive substances	Radon-222, iodine-131, strontium-90, plutonium-239 (Table 3-2, p. 62)
Hazardous air pollutants (HAPs), which cause health effects such as cancer, birth defects, and nervous system problems	Carbon tetrachloride (CCl <sub>4</sub> ), methyl chloride (CH <sub>3</sub> Cl), chloroform (CHCl <sub>3</sub> ), benzene (C <sub>6</sub> H <sub>6</sub> ), ethylene dibromide (C <sub>2</sub> H <sub>2</sub> Br <sub>2</sub> ), formaldehyde (CH <sub>2</sub> O <sub>2</sub> )

Most outdoor pollutants in urban areas enter the atmosphere from the burning of fossil fuels in power plants and factories (*stationary sources*) and motor vehicles (*mobile sources*). According to the World Bank and the United Nations, (1) burning coal to produce electricity is responsible for 67% of SO<sub>2</sub>, 36% of CO<sub>2</sub>, 33% of mercury, and 28% of NO<sub>x</sub> emissions each year in the United States and (2) vehicle emissions account for 75% of CO, 33% of CO<sub>2</sub>, and 44% of NO<sub>x</sub> in U.S. urban air. In car-clogged cities such as Los Angeles, California; São Paulo, Brazil; Bangkok, Thailand (Figure 11-1, p. 238); Rome, Italy; and Mexico City, Mexico (Case Study, p. 660), motor vehicles are responsible for 80–88% of the air pollution.

**Primary pollutants** are those emitted directly into the troposphere in a potentially harmful form. While in the troposphere, some of these primary pollutants may react with one another or with the basic components of air to form new pollutants, called **secondary pollutants** (Figure 17-4).

With their large concentrations of cars and factories, cities normally have higher air pollution levels than rural areas. However, prevailing winds can spread long-lived primary and secondary air pollutants emitted in urban and industrial areas to the countryside and to other downwind urban areas.

Indoor pollutants come from (1) infiltration of polluted outside air and (2) various chemicals used or produced inside buildings, as discussed in more detail in Section 17-5. Risk analysis experts rate indoor and outdoor air pollution as high-risk human health problems (Figure 16-13, left, p. 411).

According to the World Health Organization (WHO), more than 1.1 billion people—one of every five—live in urban areas where the air is unhealthy to breathe. Most live in densely populated cities in developing countries where air pollution control laws do not exist or are poorly enforced.

In the United States (and in most other countries), government-mandated standards set maximum allowable atmospheric concentrations for six *criteria air pollutants* commonly found in outdoor air (Table 17-2).

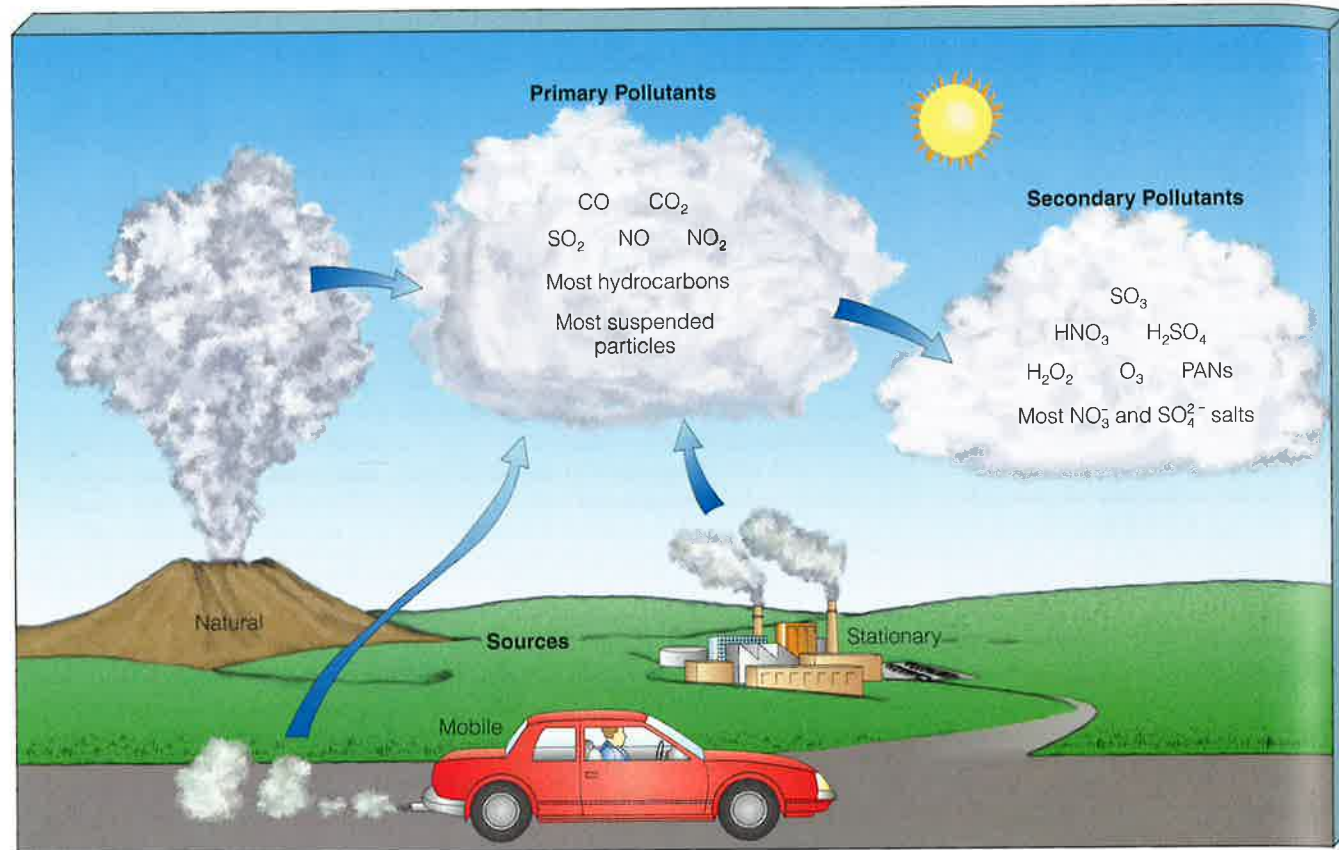
## 17-3 PHOTOCHEMICAL AND INDUSTRIAL SMOG

### What Is Photochemical Smog? Brown-Air Smog?

Any chemical reaction activated by light is called a *photochemical reaction*. Air pollution known as **photochemical smog** is a mixture of primary and secondary pollutants formed under the influence of sunlight (Figure 17-5, p. 424). The resulting mixture of more than 100 chemicals is dominated by *ozone*, a highly reactive gas that harms most living organisms (Figure 17-3).

Here is a simplified version of the complex chemistry of photochemical smog formation. It begins when nitrogen and oxygen in air react at the high temperatures found inside automobile engines and the boilers in coal-burning power and industrial plants to produce colorless nitric oxide ( $\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$ ). Once in the troposphere, the nitric oxide slowly reacts with oxygen to form nitrogen dioxide, a yellowish-brown gas with a choking odor ( $2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$ ). The NO<sub>2</sub>





**Figure 17-4** Sources and types of air pollutants. Human inputs of air pollutants may come from *mobile sources* (such as cars) and *stationary sources* (such as industrial and power plants). Some *primary air pollutants* may react with one another or with other chemicals in the air to form *secondary air pollutants*.

is responsible for the brownish haze that hangs over many cities during the afternoons of sunny days, explaining why photochemical smog sometimes is called *brown-air smog*.

Some of the  $\text{NO}_2$  reacts with water vapor in the atmosphere to form nitric acid vapor and nitric oxide ( $3\text{NO}_2 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_3 + \text{NO}$ ). When the remaining  $\text{NO}_2$  is exposed to ultraviolet radiation from the sun, some of it is converted to nitric oxide and oxygen atoms ( $\text{NO}_2 + \text{UV radiation} \rightarrow \text{NO} + \text{O}$ ). The highly reactive oxygen atoms then react with  $\text{O}_2$  to produce ozone ( $\text{O}_2 + \text{O} \rightarrow \text{O}_3$ ). Both the oxygen atoms and ozone then react with volatile organic compounds (mostly hydrocarbons released by vegetation, vehicles, gas stations, oil refineries, and dry cleaners) to produce aldehydes. In addition, hydrocarbons, oxygen, and nitrogen dioxide react to produce peroxyacyl nitrates, or PANs (hydrocarbons +  $\text{O}_2 + \text{NO}_2 \rightarrow \text{PANs}$ ).

Collectively,  $\text{NO}_2$ ,  $\text{O}_3$ , and PANs are called *photochemical oxidants* because they can react with and oxidize certain compounds in the atmosphere (or inside your lungs) that normally are not oxidized. Mere traces of these photochemical oxidants (especially ozone) and aldehydes in photochemical smog can irritate the respiratory tract and damage crops and trees.

The hotter the day, the higher the levels of ozone and other components of photochemical smog. As traffic increases in the morning, levels of  $\text{NO}_x$  and unburned hydrocarbons rise and begin reacting in the presence of sunlight to produce photochemical smog. On a sunny day the photochemical smog (dominated

by  $\text{O}_3$ ) builds up to peak levels by early afternoon, irritating people's eyes and respiratory tracts (Figure 17-6).

All modern cities have photochemical smog, but it is much more common in cities with sunny, warm, dry climates and lots of motor vehicles. Examples of such cities are Los Angeles, California; Denver, Colorado; and Salt Lake City, Utah in the United States, as well as Sydney, Australia; Mexico City, Mexico; and São Paulo and Buenos Aires in Brazil. According to a 1999 article in *Geophysical Research Letters*, if 400 million Chinese drivers drive cars by 2050 as projected, the resulting photochemical smog could cover the entire western Pacific in ozone, extending to the United States.

High levels of ozone have also been measured above the tropical forests of the Amazon basin, where cars are not the culprit. In this case, hydrocarbons naturally released by the trees and other vegetation can interact with natural levels of  $\text{NO}_2$  and sunlight to produce ozone. In 2000, researchers at the University of California at Irvine found that atmospheric particles of sea salt ( $\text{NaCl}$ ) can be converted by sunlight into chlorine atoms. When these highly reactive Cl atoms come in contact with pollutants emitted from fossil fuel combustion they can form ground-level ozone.

**What Is Industrial Smog? Gray-Air Smog** Fifty years ago cities such as London, England, and Chicago and Pittsburgh in the United States burned large amounts of coal and heavy oil (which contain sulfur impurities; Figure 14-27, p. 344) in power plants and factories and for space heating. During winter, people

**Table 17-2 Common Criteria Air Pollutants in the United States**

#### CARBON MONOXIDE ( $\text{CO}$ )

**Description:** Colorless, odorless gas that is poisonous to air-breathing animals; forms during the incomplete combustion of carbon-containing fuels ( $\text{C} + \text{O}_2 \rightarrow 2\text{CO}$ ).

##### Major human sources:

Cigarette smoking (p. 396), incomplete burning of fossil fuels. About 77% (95% in cities) comes from motor vehicle exhaust.

**Health effects:** Reacts with hemoglobin in red blood cells and reduces the ability of blood to bring oxygen to body cells and tissues. This impairs perception and thinking; slows reflexes; causes headaches, drowsiness, dizziness, and nausea; can trigger heart attacks and angina; damages the devel-

opment of fetuses and young children; and aggravates chronic bronchitis, emphysema, and anemia. At high levels it causes collapse, coma, irreversible brain cell damage, and death.

#### NITROGEN DIOXIDE ( $\text{NO}_2$ )

**Description:** Reddish-brown, irritating gas that gives photochemical smog its brownish color; in the atmosphere can be converted to nitric acid ( $\text{HNO}_3$ ), a major component of acid deposition.

**Major human sources:** Fossil fuel burning in motor vehicles (49%) and power and industrial plants (49%).

**Health effects:** Lung irritation and damage; aggravates asthma and chronic bronchitis; increases susceptibility to

respiratory infections such as the flu and common colds (especially in young children and older adults).

##### Environmental effects:

Reduces visibility; acid deposition of  $\text{HNO}_3$  can damage trees, soils, and aquatic life in lakes.

**Property damage:**  $\text{HNO}_3$  can corrode metals and eat away stone on buildings, statues, and monuments;  $\text{NO}_2$  can damage fabrics.

#### SULFUR DIOXIDE ( $\text{SO}_2$ )

**Description:** Colorless, irritating; forms mostly from the combustion of sulfur-containing fossil fuels such as coal and oil ( $\text{S} + \text{O}_2 \rightarrow \text{SO}_2$ ); in the atmosphere can be converted to sulfuric acid ( $\text{H}_2\text{SO}_4$ ), a major component

of acid deposition.

**Major human sources:** Coal burning in power plants (88%) and industrial processes (10%).

**Health effects:** Breathing problems for healthy people; severe restriction of airways in people with asthma; chronic exposure can cause a permanent condition similar to bronchitis. According to the World Health Organization, at least 625 million people are exposed to unsafe levels of sulfur dioxide from fossil fuel burning.

**Environmental effects:** Reduces visibility; acid deposition of  $\text{H}_2\text{SO}_4$  can damage trees, soils, and aquatic life in lakes.

**Property damage:**  $\text{SO}_2$  and  $\text{H}_2\text{SO}_4$  can corrode metals

and eat away stone on buildings, statues, and monuments;  $\text{SO}_2$  can damage paint, paper, and leather.

#### SUSPENDED PARTICULATE MATTER (SPM)

**Description:** Variety of particles and droplets (aerosols) small and light enough to remain suspended in atmosphere for short periods (large particles) to long periods (small particles; Figure 17-7); we see these particles as smoke, dust, and haze.

##### Major human sources:

Burning coal in power and industrial plants (40%), burning diesel and other fuels in vehicles (17%), agriculture (plowing, burning off fields), unpaved roads, construction.

**Health effects:** Nose and

throat irritation, lung damage, and bronchitis; aggravates bronchitis and asthma; causes early death; toxic particulates (such as lead, cadmium, PCBs, and dioxins) can cause mutations, reproductive problems, or cancer.

**Environmental effects:** Reduces visibility; acid deposition of  $\text{H}_2\text{SO}_4$  droplets can damage trees, soils, and aquatic life in lakes.

**Property damage:** Corrodes metal; soils and discolors buildings, clothes, fabrics, and paints.

#### OZONE ( $\text{O}_3$ )

**Description:** Highly reactive, irritating gas with an unpleasant odor that forms in the troposphere as a major compo-

nent of photochemical smog (Figures 17-5 and 17-6).

##### Major human sources:

Chemical reaction with volatile organic compounds (VOCs, emitted mostly by cars and industries) and nitrogen oxides to form photochemical smog (Figure 17-5).

**Health effects:** Breathing problems; coughing; eye, nose, and throat irritation; aggravates chronic diseases such as asthma, bronchitis, emphysema, and heart disease; reduces resistance to colds and pneumonia; may speed up lung tissue aging.

##### Environmental effects:

Ozone can damage plants and trees; smog can reduce visibility.

**Property damage:** Damages rubber, fabrics, and paints.

#### LEAD

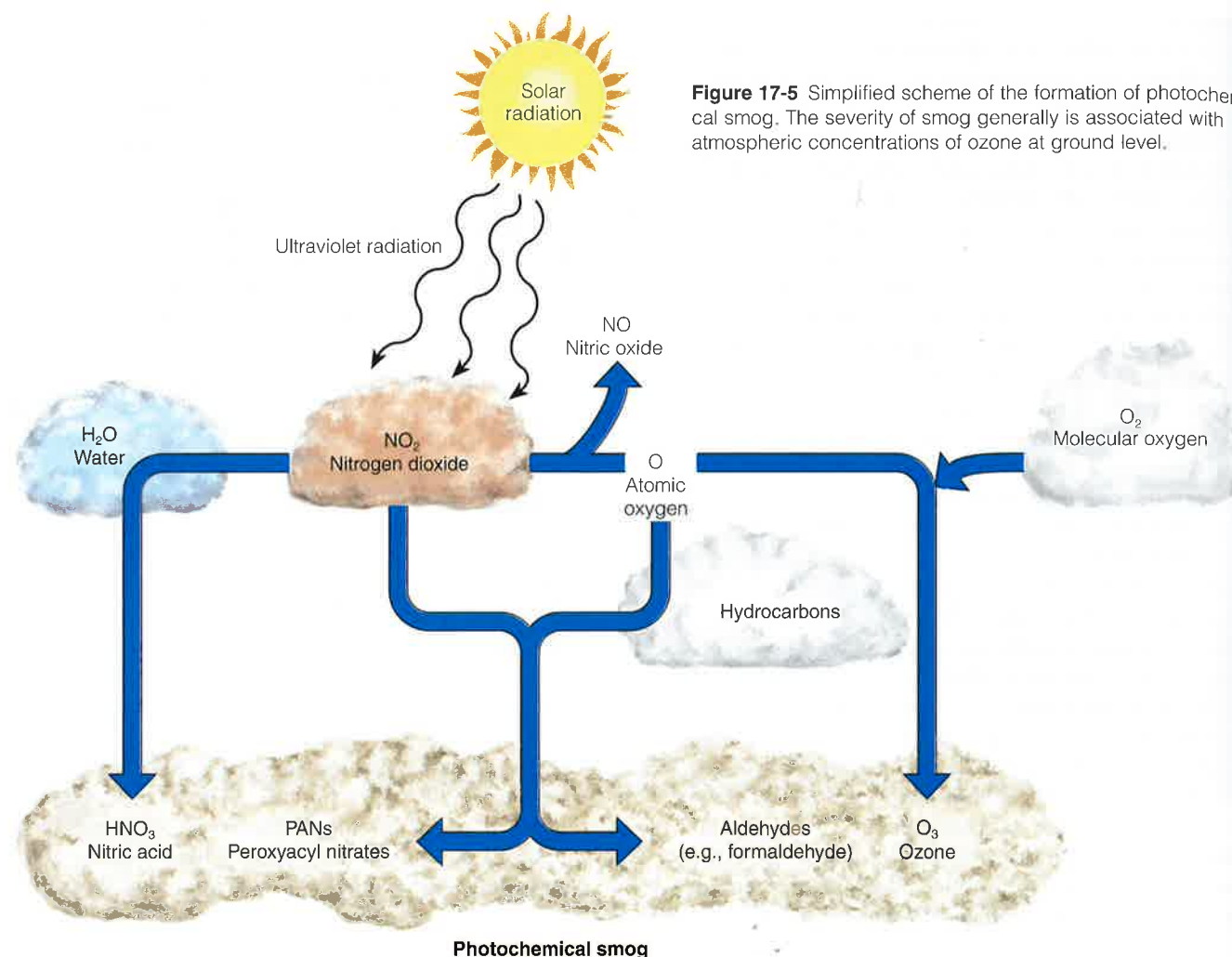
**Description:** Solid toxic metal and its compounds, emitted into the atmosphere as particulate matter.

**Major human sources:** Paint (old houses), smelters (metal refineries), lead manufacture, storage batteries, leaded gasoline (being phased out in developed countries).

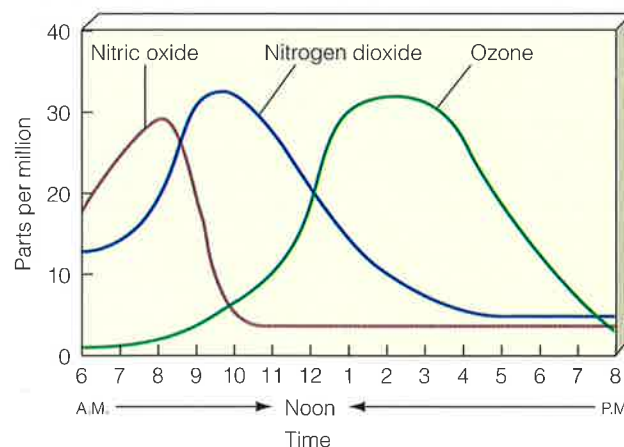
**Health effects:** Accumulates in the body; brain and other nervous system damage and mental retardation (especially in children); digestive and other health problems; some lead-containing chemicals cause cancer in test animals.

**Environmental effects:** Can harm wildlife. Data from U.S. Environmental Protection Agency.





**Figure 17-5** Simplified scheme of the formation of photochemical smog. The severity of smog generally is associated with atmospheric concentrations of ozone at ground level.



**Figure 17-6** Typical daily pattern of changes in concentrations of air pollutants that lead to development of photochemical smog in a city such as Los Angeles, California. (From *Environmental Science*, 5/E by Chiras, p. 363. Copyright ©2000 by Wadsworth)

in such cities were exposed to **industrial smog** consisting mostly of (1) sulfur dioxide, (2) suspended droplets of sulfuric acid (formed from some of the sulfur dioxide, Figure 17-4), and (3) a variety of suspended solid particles and droplets (called aerosols; Figure 17-7).

The chemistry of industrial smog is fairly simple. When burned, the carbon in coal and oil is converted to

carbon dioxide ( $C + O_2 \rightarrow CO_2$ ) and carbon monoxide ( $2C + O_2 \rightarrow 2CO$ ). Some of the unburned carbon also ends up in the atmosphere as suspended particulate matter (soot).

The sulfur compounds in coal and oil also react with oxygen to produce sulfur dioxide, a colorless, suffocating gas ( $S + O_2 \rightarrow SO_2$ ). Sulfur dioxide also is emitted into the troposphere when metal sulfide ores (such as lead sulfide,  $PbS$ ) are roasted or smelted to convert the metal ore to the free metal (Figure 14-8, p. 327).

In the troposphere, some of the sulfur dioxide reacts with oxygen to form sulfur trioxide ( $2SO_2 + O_2 \rightarrow 2SO_3$ ), which then reacts with water vapor in the air to produce tiny suspended droplets of sulfuric acid ( $SO_3 + H_2O \rightarrow H_2SO_4$ ). Some of these

droplets react with ammonia in the atmosphere to form solid particles of ammonium sulfate ( $2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$ ). The tiny suspended particles of such salts and carbon (soot) give the resulting industrial smog a gray color, explaining why it is sometimes called *gray-air smog*.

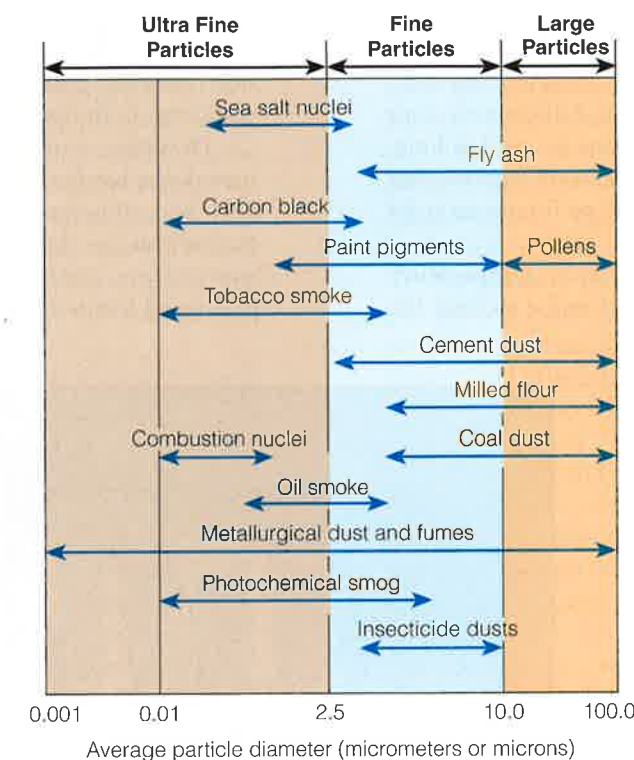
Urban industrial smog is rarely a problem today in most developed countries because coal and heavy oil are burned only in large boilers with reasonably good pollution control or with tall smokestacks (which transfer the pollutants to downwind areas). However, industrial smog is a problem in industrialized urban areas of China, India, Ukraine, and some eastern European countries, where large quantities of coal are burned with inadequate pollution controls.

For example, the world's 10 most air-polluted cities are found in China (9 cities) and India (1 city), mostly because of heavy use of coal. An estimated 800 million of China's 1.2 billion people burn coal in their homes for cooking and heating, often in unvented stoves that fill their homes with toxic fumes. Globally, indoor air pollution from such coal burning accounts for about 2.8 million of the estimated 3 million people who die prematurely each year from air pollution.

**What Factors Influence the Formation of Photochemical and Industrial Smog?** The frequency and severity of smog in an area depend on (1) local climate and topography, (2) population density, (3) the amount of industry, and (4) the fuels used in industry, heating, and transportation.

Air pollution can be reduced by:

- **Rain and snow**, which help cleanse the air of pollutants. This explains why cities with dry climates are more prone to photochemical smog than ones with wet climates.
- **Winds**, which help sweep pollutants away, dilute pollutants by mixing them with cleaner air, and bring in fresh air.



**Figure 17-7** Suspended particulate matter consists of particles of solid matter and droplets of liquid that are small and light enough to remain suspended in the atmosphere for short periods (large particles) to long periods (small particles). Suspended particles are found in a wide variety of types and sizes, ranging from 0.001 micrometer to 100 micrometers (a micrometer, or micron, is one millionth of a meter, or about 0.00004 inches). Since 1987, the EPA has focused on *fine particles* smaller than 10 microns (known as *PM-10*). In 1997, the agency began focusing on reducing emissions of *ultrafine particles* with diameters less than 2.5 microns (known as *PM-2.5*) because these particles are small enough to reach the lower part of human lungs and contribute to respiratory diseases.

Wind and rain can help cleanse urban air, but because of the law of conservation of matter (p. 60), the pollutants do not disappear. They are blown somewhere else or are deposited from the sky onto surface waters, soil, and buildings.

In addition, a 2000 study of clean and dirty clouds over three countries by atmospheric scientist Daniel Rosenfield indicated that air pollution can reduce the rain and snowfall that help cleanse the air of pollutants. He found that clean clouds hold large droplets of water that can easily be converted into rain or snow. However, dirty clouds contain small water droplets that are less likely to bump into each other and stick together in large enough clumps to form air-cleansing raindrops and snowflakes.

Three factors that can increase air pollution are:

- **Urban buildings** that can slow wind speed and reduce dilution and removal of pollutants.
- **Hills and mountains** that tend to reduce the flow of air in valleys below them

and allow pollutant levels to build up at ground level.

- **High temperatures** that promote the chemical reactions that lead to photochemical smog formation.

**What Are Temperature Inversions?** During daylight the sun warms the air near the earth's surface. Normally, this warm air and most of the pollutants it contains rises to mix with the cooler air above it. This mixing of warm and cold air creates turbulence, which disperses the pollutants.

Under certain atmospheric conditions, however, a layer of warm air can lie atop a layer of cooler air nearer the ground, a situation known as a **temperature inversion**. Because the cooler air is denser than the warmer air above it, the air near the surface does not rise and mix with the air above it. Pollutants can concentrate in this stagnant layer of cool air near the ground.

There are two types of temperature inversions. One, called a **subsidence temperature inversion**,

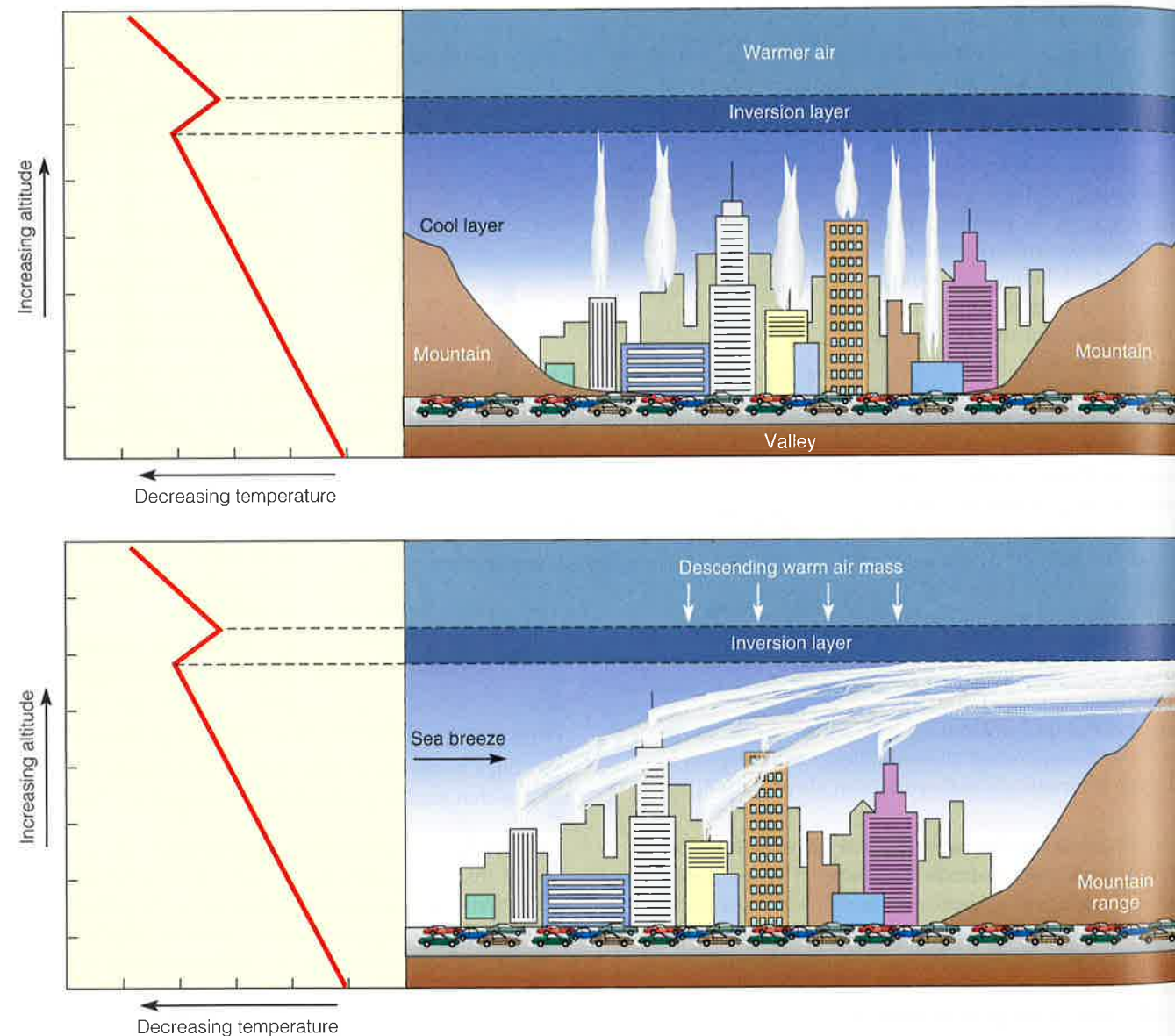


occurs when a large mass of warm air moves into a region at a high altitude and floats over a mass of colder air near the ground. This keeps the air over a city stagnant and prevents vertical mixing and dispersion of air pollutants. Normally such conditions do not last long, but sometimes warmer air masses can remain over cooler air below for days and allow pollutants to build up to harmful levels.

The second type, called a **radiation temperature inversion**, typically occurs at night as the air near the

ground cools faster than the air above it. As the sun rises and warms the earth's surface, a radiation inversion normally disappears by noon and disperses the pollutants built up during the night.

However, under certain conditions, radiation or subsidence temperature inversions can last for several days and allow pollutants to build up to dangerous concentrations. Areas with two types of topography and weather conditions are especially susceptible to prolonged temperature inversions (Figure 17-8).



**Figure 17-8** Topography and weather conditions that can create more frequent and prolonged *radiation temperature inversions*, in which a layer of warm air sits atop a cooler layer of air near the ground. In such cases, pollutant concentrations in the air near the earth's surface can build up to harmful levels. The left figure shows how air pollutants can build up in the air near the ground in a valley surrounded by mountains. The right figure shows how frequent and prolonged radiation temperature inversions can occur in an area (such as Los Angeles, California) with a sunny climate, light winds, mountains on three sides, and the ocean on the other. The layer of descending warm air (right) prevents ascending air currents from dispersing and diluting pollutants from the cooler air near the ground. Because of their topography, Los Angeles in the United States and Mexico City in Mexico have frequent thermal inversions, many of them prolonged during the summer.

One such area is a town or city located in a valley surrounded by mountains that experiences cloudy and cold weather during part of the year (Figure 17-8, top). In such cases, the surrounding mountains block out the winter sun needed to reverse the nightly radiation temperature inversion. As long as these stagnant conditions persist, concentrations of pollutants in the valley below will build up to harmful and even lethal concentrations. This is what happened during the 1948 air pollution disaster in the valley town of Donora, Pennsylvania (Spotlight, p. 420).

A city with several million people and motor vehicles in an area with a (1) sunny climate, (2) light winds, (3) mountains on three sides, and (4) the ocean on the other has ideal conditions for photochemical smog worsened by frequent subsidence thermal inversions (Figure 17-8, bottom). This describes California's heavily populated Los Angeles basin, which has prolonged subsidence temperature inversions at least half of the year, mostly during the warm summer and fall months. High-pressure air off the coast of California much of the year creates a descending warm air mass that sits atop an air mass below that is cooled by the nearby ocean. When this subsidence thermal inversion persists throughout the day, the surrounding mountains prevent the polluted surface air from being blown away by sea breezes (Figure 17-8, bottom).

## 17-4 REGIONAL OUTDOOR AIR POLLUTION FROM ACID DEPOSITION

### What Is an Acid, and How Is Acidity Measured?

An **acid** is any chemical that releases hydrogen ions ( $H^+$ ) when dissolved in water. Examples of acids include hydrochloric acid ( $HCl$ ), nitric acid ( $HNO_3$ ), sulfuric acid ( $H_2SO_4$ ), and carbonic acid ( $H_2CO_3$ ). The higher the concentration of hydrogen ions in a solution, the more acidic the solution.

A numerical scale of pH values is commonly used to express hydrogen ion concentrations. The lower the pH of a water solution, the greater its acidity. Solutions with pH values less than 7 are *acidic*, and those with pH values greater than 7 are *alkaline* or *basic* (Figure 3-7, p. 56).

Each whole number change on the pH scale represents a tenfold change in the concentration of hydrogen ions in a water solution. For example, a solution with a pH of 4 is 10 times as acidic (has 10 times as many  $H^+$  ions per unit of volume) as one with a pH of 5 and 100 times as acidic as a solution with a pH of 6. How many times as acidic is a solution with a pH of 2 as a solution with a pH of 6?

Water and carbon dioxide in the atmosphere react to produce a weakly acidic solution of carbonic acid ( $H_2O + CO_2 \rightarrow H_2CO_3$ ). As a result, natural rainfall has a pH of about 5.6 (Figure 3-7, p. 56).

**What Is Acid Deposition?** Most coal-burning power plants, ore smelters, and other industrial plants in developed countries use tall smokestacks to emit sulfur dioxide, suspended particles, and nitrogen oxides above the inversion layer (Figure 17-8), where mixing, dilution, and removal by wind are more effective. Thus, tall smokestacks reduce *local* air pollution but increase *regional* air pollution downwind.

The primary pollutants, sulfur dioxide and nitrogen oxides, emitted into the atmosphere above the inversion layer are transported as much as 1,000 kilometers (600 miles) by prevailing winds. During their trip, they form secondary pollutants such as nitric acid vapor, droplets of sulfuric acid, and particles of acid-forming sulfate and nitrate salts (Figure 17-4).

These acidic substances remain in the atmosphere for 2-14 days, depending mostly on prevailing winds, precipitation, and other weather patterns. During this period they descend to the earth's surface in two forms: (1) *wet deposition* (as acidic rain, snow, fog, and cloud vapor with a pH less than 5.6) and (2) *dry deposition* (as acidic particles). The resulting mixture is called **acid deposition** (Figure 17-9), sometimes called *acid rain*. Most dry deposition occurs within about 2-3 days fairly near the emission sources, whereas most wet deposition occurs takes place in 4-14 days in more distant downwind areas (Figure 17-9).

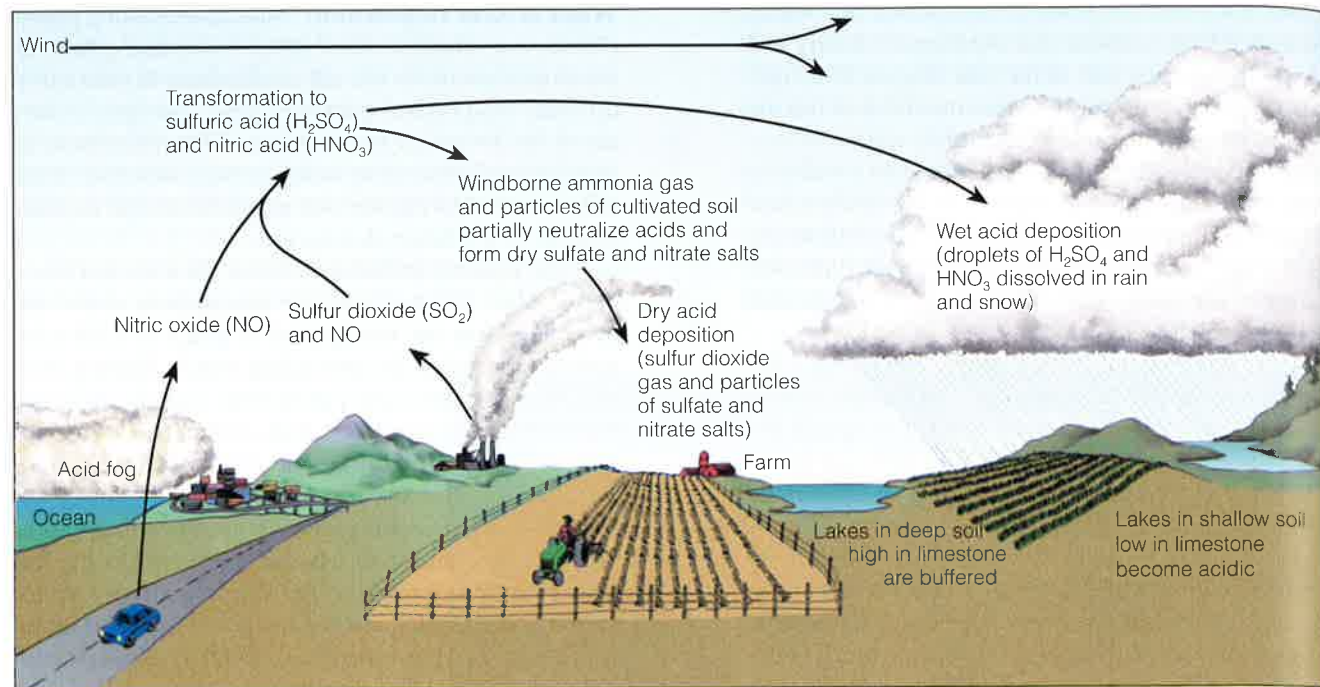
**What Areas Are Most Affected by Acid Deposition?** Acid deposition is a regional problem in the eastern United States (Figure 17-10) and in other parts of the world (Figure 17-11). Most of these regions are downwind from coal-burning power plants, smelters, or factories or are major urban areas with large numbers of motor vehicles.

In the United States, coal-burning power and industrial plants in the Ohio Valley (Figure 17-10) emit the largest quantities of sulfur dioxide and other acidic pollutants. Mostly as a result of these emissions, typical precipitation in the eastern United States has a pH of 4.2 to 4.7 (Figure 17-10), 10 or more times the acidity of natural precipitation with a pH of 5.6. Some mountaintop forests in the eastern United States and east of Los Angeles, California, are bathed in fog and dew as acidic as lemon juice, with a pH of 2.3—about 1,000 times the acidity of normal precipitation.

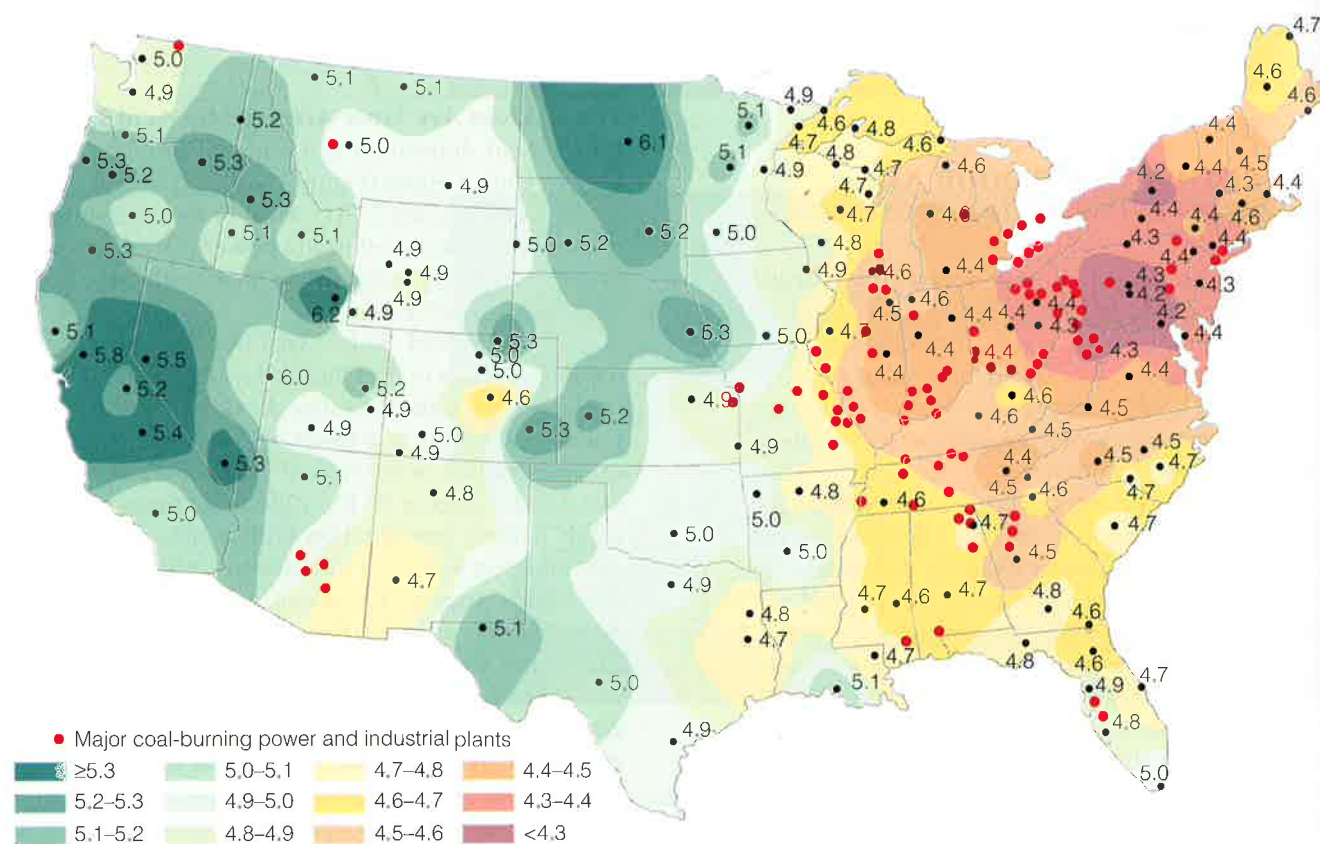
A **buffer** is a substance that can react with hydrogen ions in a solution and thus hold the pH fairly constant. Calcium carbonate ( $CaCO_3$ ), or limestone, is a natural buffer that protects many soils and lakes from acid precipitation. Hydrogen ions in acids percolating through soils derived from limestone rock are neutralized (buffered) when they react with  $CaCO_3$  ( $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$ ).

The areas most sensitive to acid deposition are (1) those containing thin, acidic soils derived mostly from granitic rock without such natural buffering





**Figure 17-9** Acid deposition, which consists of rain, snow, dust, or gas with a pH lower than 5.6, is commonly called acid rain. Soils and lakes vary in their ability to buffer or remove excess acidity.



**Figure 17-10** pH values from field measurements in 48 states in 1998. Red dots show major sources of sulfur dioxide ( $\text{SO}_2$ ) emissions, mostly large coal-burning power plants. In the eastern United States, the primary component of acid deposition is  $\text{H}_2\text{SO}_4$  (formed from  $\text{SO}_2$  emitted by coal-burning plants). In the western United States,  $\text{HNO}_3$  predominates (formed mostly from  $\text{NO}_x$  emissions from motor vehicles). (National Atmospheric Deposition Program [NRSP-3]/National Trends Network, 1998. NADP Program Office, Illinois State Water Survey, 2204 Griffith Dr., Champaign, IL 61820)

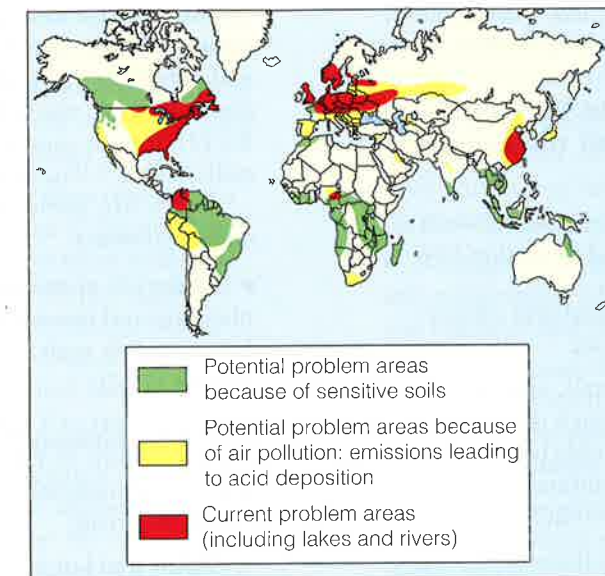
(Figure 17-11, green and most red areas) and (2) those in which the buffering capacity of soils has been depleted by decades of acid deposition (some red areas in Figure 17-11).

Many acid-producing chemicals generated by power plants, factories, smelters, and cars in one country are exported to other countries by prevailing winds. For example, studies show that some acid deposition in:

- Norway, Switzerland, Austria, Sweden, the Netherlands, and Finland is blown to those countries from industrialized areas of western Europe (especially the United Kingdom and Germany) and eastern Europe.

- Southeastern Canada (Figure 17-11) can be traced to  $\text{SO}_2$  and other emissions from the Ohio Valley of the United States (Figure 17-10).

- The eastern United States has been traced to emissions from two large metal smelters in southeastern Canada.
- Japan and North and South Korea comes from China.

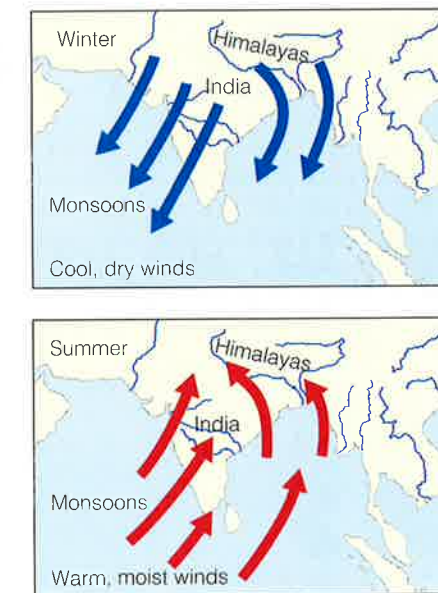
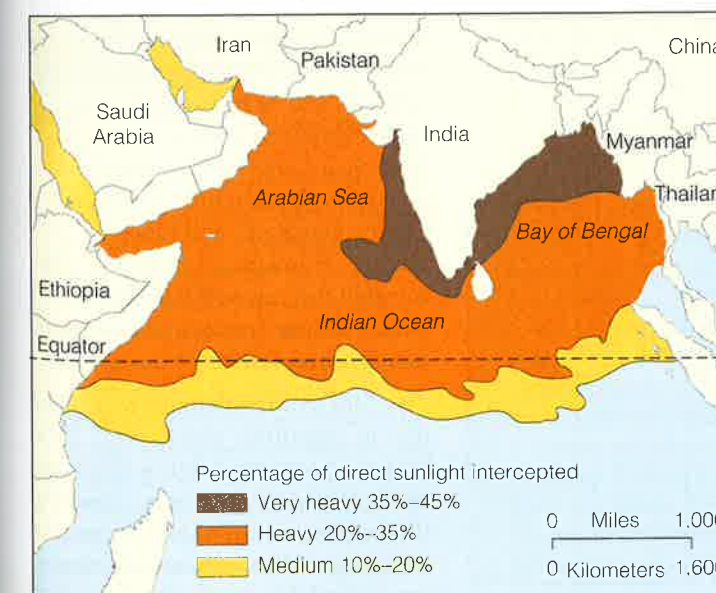


**Figure 17-11** Regions where acid deposition is now a problem (red) and regions with the potential to develop this problem (yellow). Such regions have (1) large inputs of air pollution (mostly from power plants, industrial plants, and ore smelters, red dots in Figure 17-10) or (2) sensitive areas with soils and bedrock that cannot neutralize (buffer) inputs of acidic compounds (green areas and most red areas). (Data from World Resources Institute and U.S. Environmental Agency)

The worst acid deposition is in Asia, especially in China, which gets 73% of its energy from burning coal. Acid deposition already affects more than one-fourth of China's land area and could increase over the next two decades because of projected increases in  $\text{SO}_2$  and  $\text{NO}_x$  emissions. This could (1) overwhelm many of the country's soils, (2) reduce crop productivity (Case Study, p. 272), and (3) hinder efforts to restore deforested areas. Acid deposition is also a growing problem in eastern Europe, Russia, Nigeria, Venezuela, and Colombia (Figure 17-11).

In 1999, researchers at California's Scripps Institution of Oceanography found a thick, brown haze of air pollution covering much of the Indian Ocean during winter

(Figure 17-12). The haze-covered area is about the size of the United States and rises as high as 3,000 meters (10,000 feet). During the late spring and summer, when prevailing winds reverse, some of the haze



**Figure 17-12** A thick, brown haze of air pollution occurs over much of the Indian Ocean during winter. This air pollution comes from burning fossil fuels for transportation and industry in China, Southeast Asia, and India. These pollutants are blown out over the ocean during the winter monsoon season when prevailing winds flow down from the Himalayas and out to sea. In the late spring and summer, the winds reverse. This can blow some of the haze back across the land, where it can combine with monsoon rains and fall as acid deposition. (Data from Veerabhadran Ramanathan, Scripps Institution of Oceanography)

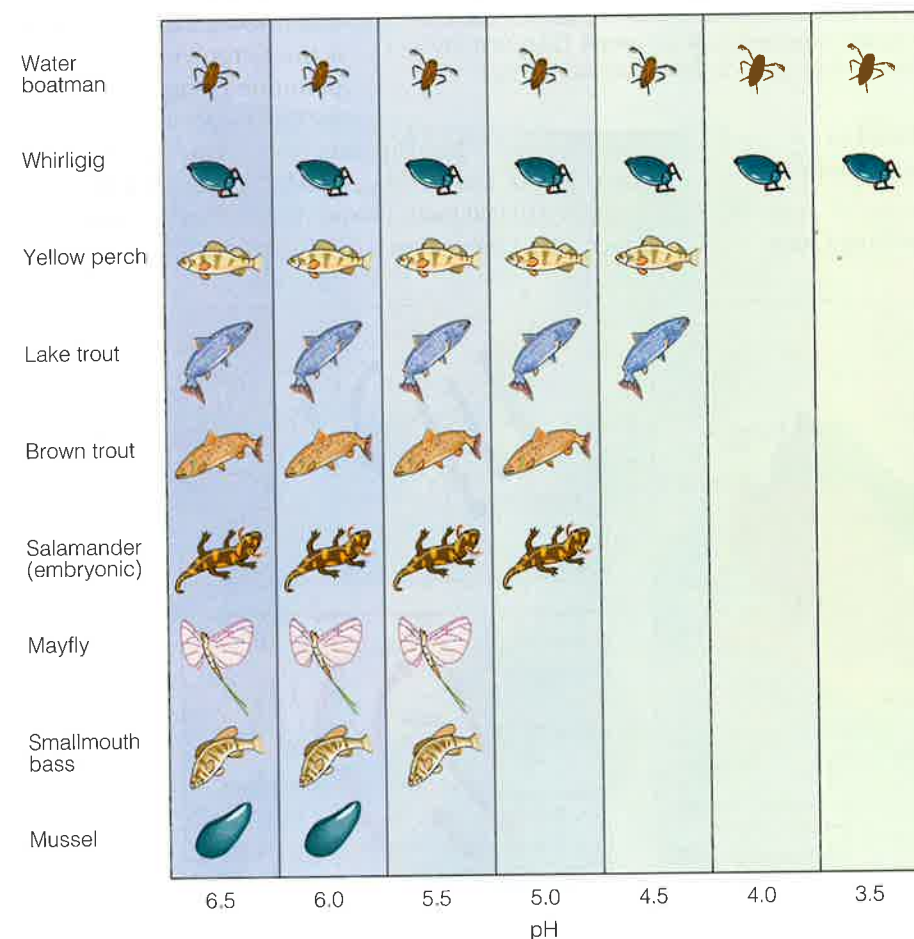


can be blown back onto the land, where it can combine with monsoon rains and fall as acid deposition.

### What Are the Effects of Acid Deposition on Human Health, Materials, and the Economy?

Acid deposition:

- Contributes to human respiratory diseases such as bronchitis and asthma, as discussed in Section 17-6.
- Can leach toxic metals such as lead and copper from water pipes into drinking water.
- Damages statues, buildings, metals, and car finishes. Limestone and marble (which is a form of limestone) are especially susceptible because they dissolve even in weak acid solutions ( $\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O}$ ).
- Decreases atmospheric visibility (mostly because of sulfate particles).
- Lowers profits and causes job losses because of lower productivity in fisheries, forests, and farms.



**Figure 17-13** Fish and other aquatic organisms vary in their sensitivity to acidity. The figure shows the lowest pH (highest acidity) at which the various species can survive. Note that the greatest effects occur when the pH drops below 5.5. (From *Environmental Science*, 5/E by Chiras, p. 393. Copyright ©2000 by Wadsworth)

### What Are the Effects of Acid Deposition on Aquatic Ecosystems?

Most freshwater lakes, streams, and ponds have a natural pH in the range of 6 to 8. Acid deposition has many harmful ecological effects when the pH of most aquatic systems falls below 6 and especially below 5 (Figure 17-13).

Here are some effects of increased acidity on aquatic systems:

- As the pH approaches 5, less desirable species of plankton and mosses may begin to invade, and populations of fish such as smallmouth bass disappear (Figure 17-13).
- Below a pH of 5, (1) fish populations begin to disappear (Figure 17-13), (2) the bottom is covered with undecayed material, and (3) mosses may dominate nearshore areas.
- Below a pH of 4.5, the water is essentially devoid of fish (Figure 17-13).
- Aluminum ions ( $\text{Al}^{3+}$ ) attached to minerals in nearby soil can be released into lakes, where they can kill many kinds of fish by stimulating excessive mucus formation. This asphyxiates the fish by clogging their gills.

■ Toxic mercury emitted by coal-burning plants can contaminate lakes, streams, and fish in downwind areas. Small aquatic organisms can transform inorganic mercury compounds deposited in lakes by air deposition or leached from nearby soils into highly toxic *methylmercury*. Methylmercury is soluble in the fatty tissue of fish. Thus, it can contaminate fish and be biomagnified to higher concentrations in aquatic food chains and webs (Figure 16-4, p. 399) and poison humans, birds, marine mammals, and other wildlife. Humans who eat the contaminated fish can suffer permanent kidney failure, tremors, severe brain damage, and death.

Much of the damage to aquatic life in sensitive areas with little buffering capacity (Figure 17-11) is a result of *acid shock*. This is caused by the sudden runoff of large amounts of highly acidic water and aluminum ions into lakes and streams, when snow melts in the spring or after unusually heavy rains.

Because of excess acidity,

- In Norway and Sweden, at least 16,000 lakes contain no fish, and

52,000 more lakes have lost most of their acid-neutralizing capacity.

- In Canada, some 14,000 acidified lakes contain few if any fish, and some fish populations in 150,000 more lakes are declining because of increased acidity.
- In the United States, about 9,000 lakes (most in the northeast and upper Midwest, Figure 17-10) are threatened with excess acidity, one-third of them seriously. According to the Environmental Protection Agency's National Surface Water Survey (NSWS), acid deposition causes about 75% of the acidic lakes and about 50% of the acidic streams in the United States.

### What Are the Effects of Acid Deposition on Plants and Soil Chemistry?

Acid deposition (often along with other air pollutants such as ozone) can harm forests and crops, especially when the soil pH falls below 5.1. Some of this injury is direct. For example, acidic substances can damage the protective waxy surface of leaves and needles. This lowers the resistance of plants to disease and allows nutrients to be leached from leaves and needles. Acid deposition can also impair germination of the seeds of trees such as spruce.

Most of the damage to forests and crops is indirect and is caused by chemical interactions in forest and cropland soils. At first, acid deposition can stimulate

tree and plant growth by adding nitrogen and sulfur nutrients to the soil. In time, however, continued inputs of these acidic chemicals can

- Leach essential plant nutrients such as calcium and magnesium salts from soils. This reduces plant productivity and the ability of the soils to buffer or neutralize acids.
- Release aluminum ions ( $\text{Al}^{3+}$ ) attached to insoluble soil compounds, which can hinder uptake and use of soil nutrients and water by plants.
- Dissolve insoluble soil compounds and release ions of metals such as lead, cadmium, and mercury that can be absorbed by plants and are highly toxic to plants and animals.
- Promote the growth of acid-loving mosses that kill trees by (1) holding so much water that feeder roots are drowned, (2) eliminating air from the soil, and (3) killing mycorrhizal fungi that help tree roots absorb nutrients.
- Weaken trees and other plants so they become more susceptible to other types of damage such as (1) severe cold, (2) diseases, (3) insect attacks, (4) drought, and (5) harmful mosses.

Many of these factors can interact synergistically to make matters worse (Connections, below).

## Hidden Synergistic Interactions and Forest Decline

**CONNECTIONS**

Loss of calcium (and magnesium) from soils can lead to several interacting, cascading, and synergistic effects. Acting over several decades, these mostly hidden interactions can escalate forest damage and decline through a positive feedback mechanism (p. 51).

Reduced calcium decreases plant productivity and the ability of the soil to neutralize (buffer) incoming acids. This in turn causes a sharp rise in soil acidification, which further depletes soil nutrients.

The increase in acidity also releases aluminum ions from the soil. This reduces the ability of tree roots to absorb remaining calcium and other soil nutrients and further decreases tree productivity.

Increased acidity can also cause a decline in earthworms, beetles, and other soil organisms that

decompose leaves and woody debris and recycle calcium and other soil nutrients (Figure 10-13, p. 221). This slows down replenishment of calcium and other plant nutrients, further aggravating forest damage and decline.

It can take decades to hundreds or thousands of years for soil development to replenish nutrients leached out by acid deposition. Thus, losses in plant productivity could continue for many decades even when air-pollution control programs reduce emissions of sulfur dioxide and nitrogen oxides.

There are other interactions. Nitrogen is often a limiting nutrient that determines the amount of plant growth for many species in terrestrial ecosystems. Until recently scientists expected some of the acid-caused loss in forest productivity to be offset by increased productivity from the larger input of nitric acid and nitrate salts from acid deposition.

However, things are not that simple. A higher nitrogen input increases the growth of certain trees and plants. However, too much nitrogen can (1) inhibit the ability of plant roots to absorb soil nutrients and (2) reduce a tree's ability to withstand cold weather. The harmful effects from excess nitrogen and increased acidity can interact synergistically to amplify plant productivity losses and tree death.

These interacting changes in soil chemistry can take place underground and remain hidden for years until at some threshold point most of a forest's dominant tree species begin dying.

**Critical Thinking**

Why should we be concerned about forest damage and decline resulting from prolonged exposure to acid deposition and other air pollutants?



Mountaintop forests are the terrestrial areas hardest hit by acid deposition because (1) they tend to have thin soils without much buffering capacity and (2) trees on mountaintops (especially conifers such as red spruce and balsam fir that keep their leaves year-round) are bathed almost continuously in very acidic fog and clouds.

Many interacting factors can decrease the health of trees (Figure 17-14 and Connections, p. 431). Any one of these stresses may be the final cause of severe tree damage or death. However, the underlying cause often is years of exposure to an atmospheric cocktail of air pollutants and soil overloaded with acids, which weakens trees and makes them more vulnerable to other stresses.

For example, scientists have analyzed decades of data on nutrient losses from soils at Yale University's

Hubbard Brook Experimental Forest in New Hampshire. They found that since 1960 acid deposition has leached out more than 50% of the available calcium in the generally alkaline (and thus buffering) soils found in this research forest. As a result, there has been no net tree growth since the 1980s.

**How Serious Is Acid Deposition in the United States?** Since 1980 the federal government has sponsored the National Acid Precipitation Assessment Program (NAPAP) to (1) coordinate government acid deposition research, (2) assess the costs, benefits, and effectiveness of the country's acid deposition legislation and control program, and (3) report its findings to Congress. In its 1998 report to Congress, the NAPAP provided both good and bad news.

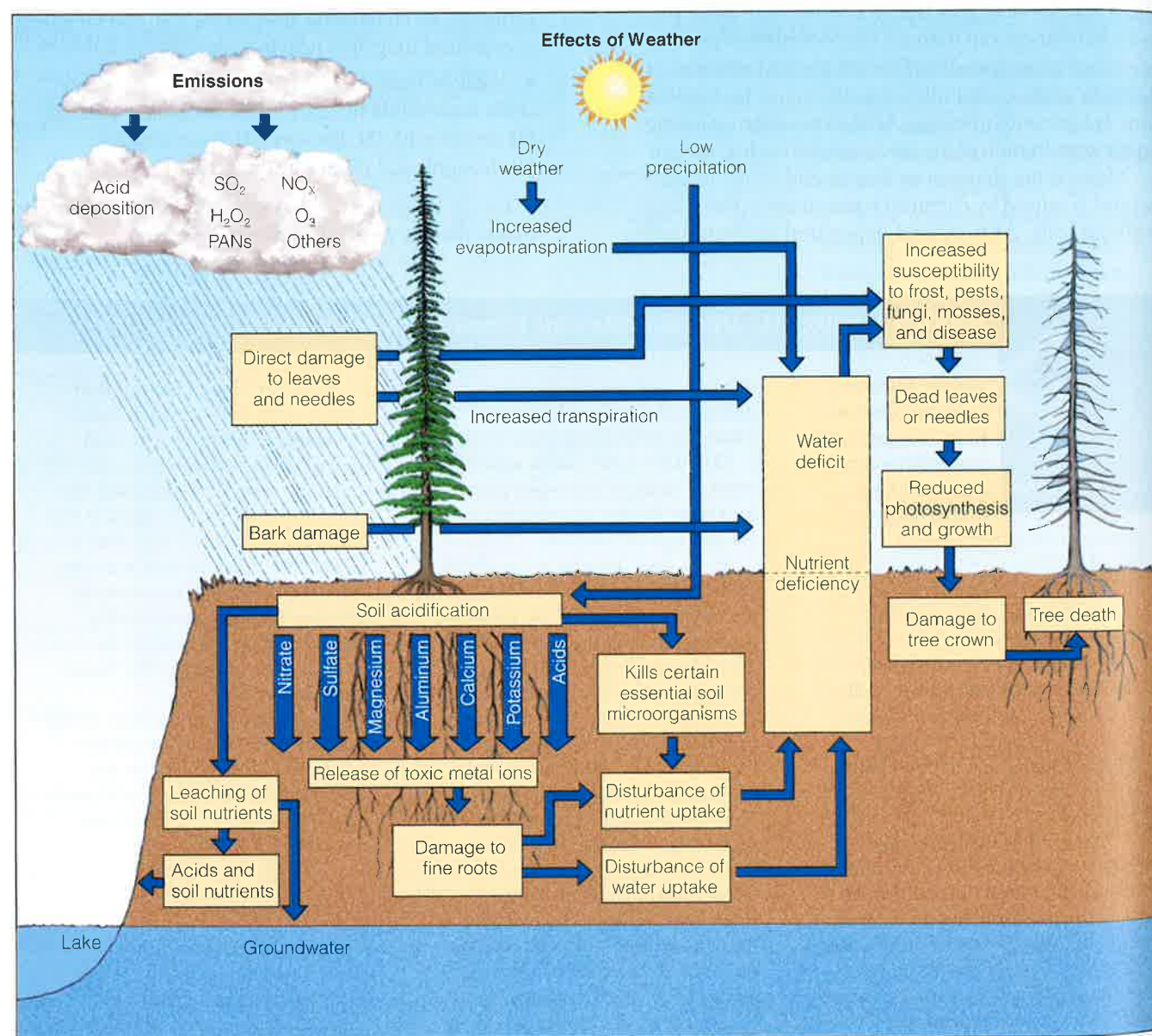


Figure 17-14 Air pollutants are one of several interacting stresses that can damage, weaken, or kill trees.

The good news is that:

- Reductions in SO<sub>2</sub> and NO<sub>x</sub> emissions from previously unregulated coal-fired power plants required by Phase I of the 1990 amendments to the Clean Air Act have been met. Although SO<sub>2</sub> emissions dropped between 1990 and 1999, NO<sub>x</sub> emissions have remained roughly the same (mostly because of emissions from motor vehicles). Phase II (which began in 2000) will require further reduction in both pollutants from a larger number of sources and will be evaluated in a 2002 report.
- There have been declines in the acidity and sulfate concentrations in precipitation in the Midwest and Northeast.
- Dissolved concentrations of sulfate (a major cause of acidification) have dropped in monitored lakes and streams.
- Epidemiological studies suggest that decreased emissions of SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter (especially fine particles) could reduce premature deaths from cardiovascular and respiratory causes.
- The magnitude of human health and visibility benefits from SO<sub>2</sub> reductions alone could exceed the costs of complying with the 1990 amendments to the Clean Air Act (but the report provides no cost-benefit calculations).

Some bad news is that:

- Deposition of sulfur and nitrogen compounds has caused adverse impacts on highly sensitive forest ecosystems in the United States.
- A scientific study of the carefully monitored Calhoun Experimental Forest in South Carolina found a 10-fold increase in acidity (a one pH unit drop) in the first 36 centimeters (14 inches) of soil and half that amount in the next 36 centimeters (14 inches) between 1962 and 1990.
- Adverse impacts from acidic deposition could develop in other forest ecosystems through chronic, long-term exposure.
- Atmospheric nitrate concentrations have not decreased.
- Although sulfate levels in many lakes have declined, there has been no decline in the acidity or acid-neutralizing capacity of sensitive aquatic systems, the key to a recovery of aquatic life.

In 1999, a team of 23 scientists (led by aquatic biologist John Stoddard) evaluated data on changes in acidity conditions in 205 lakes and streams across North America and Europe between 1980 and 1995. The good news is that (1) in seven of the eight regions studied, the concentration of dissolved sulfate declined dramatically, and (2) in Europe the drop in sulfate levels led to a decrease in acidity.

The bad news is that in four of the five regions studied in North America, there has been no drop in acidity despite dramatic drops in dissolved sulfate concentrations. According to the researchers, the soils around these lakes and deposits on their bottoms have lost much of their natural buffering capacity because acid deposition has leached out calcium and magnesium compounds. In such cases, it can take decades or centuries for this buffering capacity to be restored by weathering of underlying bedrock.

These findings were confirmed by a 2000 study by the U.S. General Accounting Office, which reported a 26% drop in sulfur deposition and a 2% increase in nitrogen deposition in the eastern states between 1989 and 1998. According to this report, "Acid rain is having a tremendously damaging effect on the Northeast."

In other words, the 1990 amendments to Clean Air Act have helped reduce some of the impacts of acid deposition in the United States. However, there is still a long way to go. According to the General Accounting Office and the EPA, the additional cuts in SO<sub>2</sub> and NO<sub>x</sub> emissions required by Phase II of the 1990 U.S. Clean Air Act will help, but sensitive lakes and soils probably will not recover without further cuts in the emissions of these two gases.

**Solutions: What Can Be Done to Reduce Acid Deposition?** Figure 17-15 summarizes ways to reduce acid deposition. According to most scientists studying acid deposition, the best solutions are *prevention approaches* that reduce or eliminate emissions of SO<sub>2</sub>, NO<sub>x</sub>, and particulates, as discussed in Section 17-7.

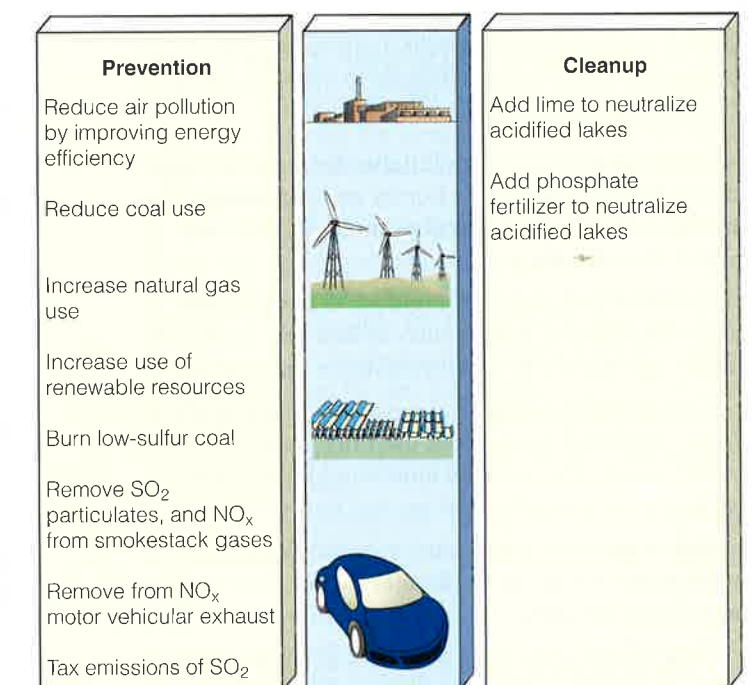


Figure 17-15 Solutions: methods for reducing acid deposition.



Controlling acid deposition is a difficult political problem because (1) the people and ecosystems it affects often are quite distant from those who cause the problem, (2) countries with large supplies of coal (such as China, India, Russia, and the United States) have a strong incentive to use it as a major energy resource, and (3) owners of coal-burning power plants say that the costs of adding air-pollution reducing equipment, using low-sulfur coal, or removing sulfur from coal are too high.

Large amounts of limestone or lime can be used to neutralize acidified lakes or surrounding soil—the only cleanup approach now being used. However, there are several problems with liming.

- It is an expensive and temporary remedy that usually must be repeated annually. Using lime to reduce excess acidity in U.S. lakes would cost at least \$8 billion per year.
- It can kill some types of plankton and aquatic plants and can harm wetland plants that need acidic water.
- It is difficult to know how much of the lime to put where (in the water or at selected places on the ground).

Recently researchers in England found that adding a small amount of phosphate fertilizer can neutralize excess acidity in a lake. However, the effectiveness of this approach is still being evaluated.

## 17-5 INDOOR AIR POLLUTION

**What Are the Types and Sources of Indoor Air Pollution?** If you are reading this book indoors, you may be inhaling more air pollutants with each breath than if you were outside (Figure 17-16). According to EPA studies, in the United States

- Levels of 11 common pollutants are generally two to five times higher inside homes and commercial buildings than outdoors and as much as 100 times higher in some cases.
- Levels of fine particles (Figure 17-7), which can contain toxins and metals such as lead and cadmium, can be as much as 60% higher indoors than outdoors.
- Concentrations of several pesticides (such as chlor-dane), approved for outdoor use only, were 10 times greater inside than outside monitored homes (some coming from pesticide dust tracked in on shoes).
- Pollution levels inside cars in traffic-clogged U.S. urban areas can be up to 18 times higher than those outside the vehicles.

The health risks from exposure to such chemicals are magnified because people typically spend 70–98% of their time indoors or inside vehicles. In 1990, the EPA

placed indoor air pollution at the top of the list of 18 sources of cancer risk, and it is rated by risk analysis scientists as a high-risk health problem for humans (Figure 16-13, left, p. 411). According to the EPA, more than 3,000 cases of cancer per year in the United States may be caused by exposure to indoor air pollutants. At greatest risk are (1) smokers, (2) infants and children under age 5, (3) the old, (4) the sick, (5) pregnant women, (6) people with respiratory or heart problems, and (7) factory workers.

Danish and U.S. EPA studies have linked pollutants found in buildings to dizziness, headaches, coughing, sneezing, nausea, burning eyes, chronic fatigue, and flu-like symptoms, known as the *sick building syndrome*. New buildings are more commonly “sick” than old ones because of reduced air exchange (to save energy) and chemicals released from new carpeting and furniture. According to the EPA, at least 17% of the 4 million commercial buildings in the United States are considered “sick” (including EPA headquarters). Indoor air pollution in the United States costs an estimated \$100 billion per year in absenteeism, reduced productivity, and health-care costs. Mostly because of differences in genetic makeup, some individuals can be acutely sensitive to one or a number of indoor air pollutants (Figure 16-3, p. 398).

According to the EPA and public health officials, the three most dangerous indoor air pollutants are (1) cigarette smoke (p. 396), (2) formaldehyde, and (3) radioactive radon-222 gas. Worker exposure to asbestos fibers in mines and in factories making asbestos material is also a serious indoor air pollution problem, especially in developing countries. A number of research studies on laboratory animals have also identified tiny fibers of *fiberglass* as a widespread and potentially potent carcinogen in indoor air.

The chemical that causes most people difficulty is *formaldehyde*, a colorless, extremely irritating gas widely used to manufacture common household materials. As many as 20 million Americans suffer from chronic breathing problems, dizziness, rash, headaches, sore throat, sinus and eye irritation, wheezing, and nausea caused by daily exposure to low levels of formaldehyde emitted (outgassed) from common household materials. These include (1) building materials (such as plywood, particleboard, paneling, and high-gloss wood used in floors and cabinets), (2) furniture, (3) drapes, (4) upholstery, (5) adhesives in carpeting and wallpaper, (6) urethane-formaldehyde insulation, (7) finger-nail hardener, and (8) wrinkle-free coating on permanent-press clothing (Figure 17-16). The EPA estimates that as many as 1 of every 5,000 people who live in manufactured homes for more than 10 years will develop cancer from formaldehyde exposure.

In developing countries, the burning of wood, dung, crop residues, and coal in open fires or in unvented or poorly vented stoves for cooking and heat-

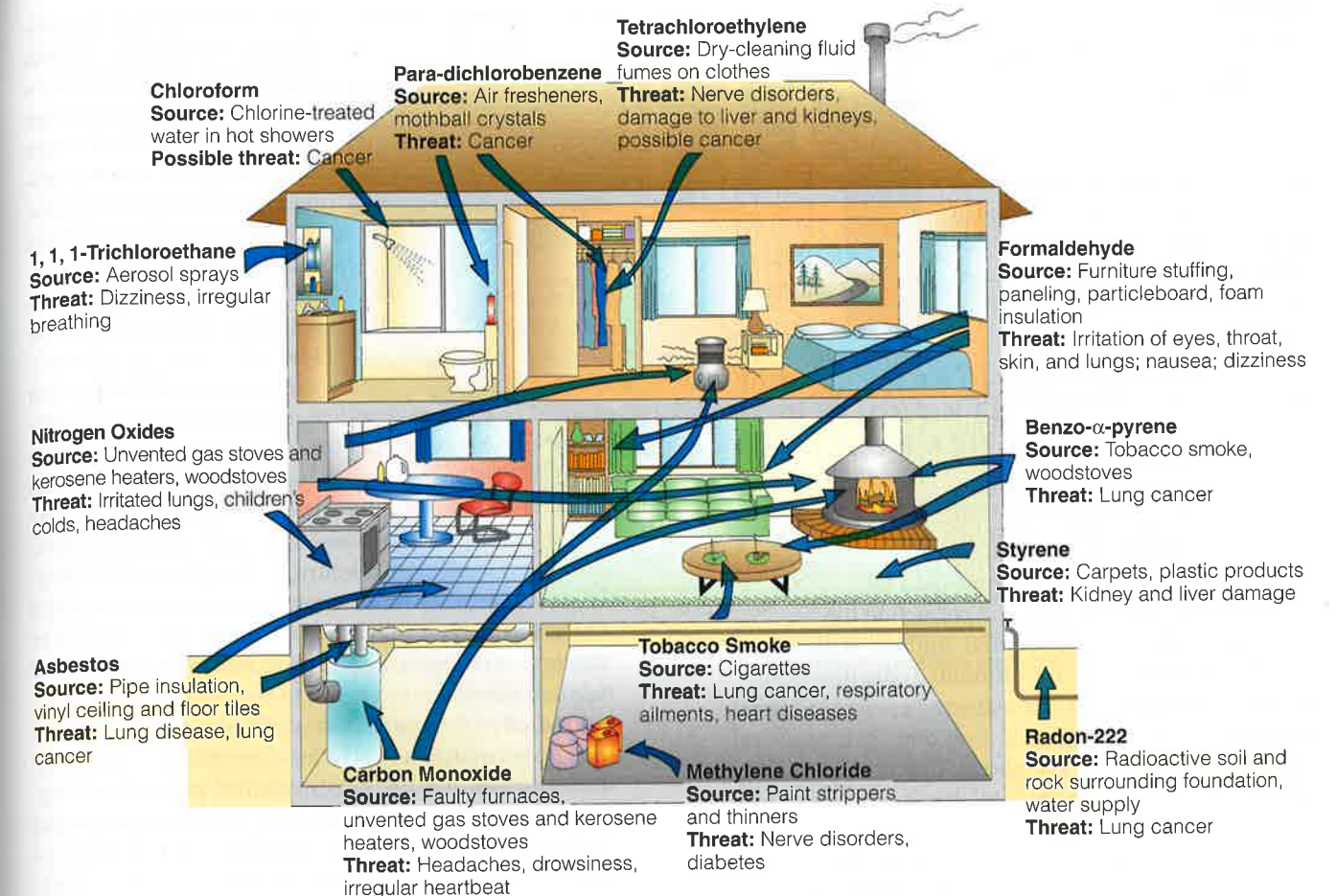


Figure 17-16 Some important indoor air pollutants. (Data from U.S. Environmental Protection Agency)

ing exposes inhabitants (especially women and young children) to very high levels of particulate air pollution.

**Case Study: Is Your Home Contaminated with Radon Gas?** Radon-222 is naturally occurring radioactive gas that you cannot see, taste, or smell. It is produced by the radioactive decay of uranium-238. Small amounts of uranium-238 are found in most soil and rock, but this isotope is much more concentrated in underground deposits of minerals such as uranium, phosphate, granite, and shale.

When radon gas from such deposits seeps upward through the soil and is released outdoors, it disperses quickly in the atmosphere and decays to harmless levels. However, radon gas can enter buildings above such deposits through (1) cracks in foundations and walls, (2) openings around sump pumps and drains, and (3) hollow concrete blocks (Figure 17-17) and build up to high levels, especially in unventilated lower levels of homes and buildings.

Radon-222 gas quickly decays into solid particles of other radioactive elements that, if inhaled, expose lung tissue to a large amount of ionizing radiation from

alpha particles (Figure 3-12, p. 62). This can damage lung tissue and lead to lung cancer over the course of a 70-year lifetime. Your chances of getting lung cancer from radon depend mostly on (1) how much radon is in your home, (2) the amount of time you spend in your home, and (3) whether you are a smoker or have ever smoked.

In 1998, the National Academy of Science estimated that prolonged exposure for a lifetime of 70 years to low levels of radon or radon acting together with smoking is responsible for 15,000 to 22,000 (or 12%) of the lung cancer deaths each year in the United States. This makes radon the second leading cause of lung cancer after smoking (p. 396). Most of the deaths are among smokers or former smokers, with about 2,100 to 2,900 among nonsmokers.

These estimates are based on assuming that (1) there is no safe threshold dose for radon exposure (Figure 16-6, left, p. 401) and that (2) the incidence of the lung cancer in uranium miners exposed to high levels of radon in mines can be extrapolated to estimate lung cancer deaths for people in homes exposed to much lower levels of radon. Some scientists question these



**Figure 17-17** Sources and paths of entry for indoor radon-222 gas. (Data from U.S. Environmental Protection Agency)

assumptions and say that these estimates are too high. They also point to the contradictory results of several epidemiological studies on the risks of lung cancer from radon exposure.

EPA indoor radon surveys suggest that 4–5 million U.S. homes may have annual radon levels above 4 picocuries per liter of air\* and that 50,000–100,000 homes may have levels above 20 picocuries per liter. If the 4 picocuries per liter standard is adopted (as proposed by the EPA), the cost of testing and correcting the problem could run about \$50 billion, with a 15–20% reduction in radon-related deaths. Some researchers argue that it makes more sense to spend perhaps only \$500 million to find and fix homes and buildings with radon levels above 20 picocuries per liter until more reliable data are available on the threat from exposure to lower levels of radon.

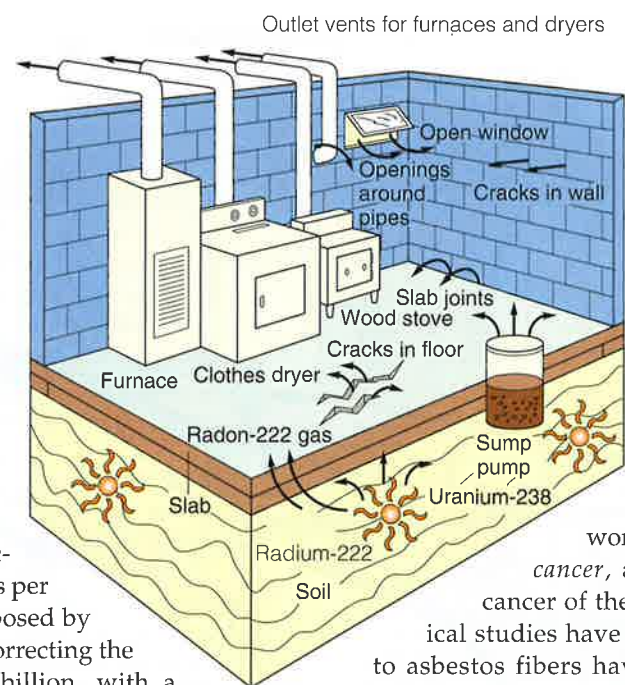
Because radon hot spots can occur almost anywhere, it is impossible to know which buildings have unsafe levels of radon without conducting tests. In 1988, the EPA and the U.S. Surgeon General's Office recommended that everyone living in a detached house, a town house, a mobile home, or on the first three floors of an apartment building test for radon. Ideally, radon levels should be monitored continuously in the main living areas (not basements or crawl spaces) for 2 months to a year. By 2000, only about 6% of U.S. households had conducted radon tests (most lasting only 2 to 7 days and costing \$20–100 per home).

If testing reveals an unacceptable level, homeowners can consult the free EPA publication *Radon Reduction Methods* for ways to reduce radon levels and health risks. According to the EPA, radon control could add \$350–500 to the cost of a new home, and correcting a radon problem in an existing house could run \$800–2,500.

#### Case Study: What Should Be Done About Asbestos?

*Asbestos* is a name given to several different fibrous forms of silicate minerals. For decades it has been widely used as a building material and for large water pipelines because of its strength, flexibility, and

\*A *picocurie* is a trillionth of a curie, which is the amount of radioactivity emitted by a gram of radium.



low cost compared to competing materials. Unless completely sealed within a product, asbestos crumbles easily into a dust of fibers tiny enough to become suspended in the air and inhaled deep into the lungs, where they remain for many years.

Prolonged exposure to asbestos fibers can cause (1) *asbestosis* (a chronic, sometimes fatal disease that makes breathing very difficult and was recognized as a hazard among asbestos workers as early as 1924), (2) *lung cancer*, and (3) *mesothelioma* (a fatal cancer of the lung's lining). Epidemiological studies have shown that smokers exposed to asbestos fibers have a much greater chance of dying from lung cancer than do nonsmokers exposed to such fibers.

Most of these diseases occur in workers exposed for years to high levels of asbestos fibers. This group includes asbestos miners, insulators, pipefitters, shipyard employees, and workers in asbestos-producing factories. Family members who breathe asbestos dust brought home in the clothes and hair of asbestos workers also have higher than expected cancer rates, as do people who live near asbestos manufacturing plants with inadequate control of asbestos emissions.

According to health officials, asbestos fibers caused the premature cancer deaths of almost 172,000 asbestos workers in the United States between 1967 and 2000, the worst occupational health disaster of the 20th century. An additional 119,000 premature cancer deaths among U.S. asbestos workers are predicted between 2000 and 2025, mostly from workers exposed to unsafe conditions before working conditions were improved.

After being swamped with health claims from workers, most U.S. asbestos manufacturing companies either declared bankruptcy or moved their operations to other countries (such as Mexico and Brazil) with weaker environmental laws and lax enforcement.

Since 1980 the focus in the United States has shifted to the possible health effects of low levels of asbestos fibers in buildings on the general public. Between 1900 and 1984, asbestos was sprayed on ceilings and walls of schools and other public and private buildings in the United States for fireproofing, soundproofing, insulation of heaters and pipes, and wall and ceiling decoration. The EPA banned those uses in 1984.

In 1989, the EPA ordered a ban on almost all remaining uses of asbestos (such as brake linings, roofing shingles, and water pipes) in the United States by

1997. Representatives of the asbestos industry in the United States and Canada (which now produces most of the asbestos used in the United States) challenged the ban in court. They contended that with proper precautions these asbestos products can be used safely and that the costs of the ban outweigh the benefits. In 1991, a federal appeals court overturned the 1989 EPA ban.

In 1979, the EPA recommended removing existing asbestos in one of every seven commercial and public buildings in the United States (including 30,000 schools), at a cost of at least \$100 billion. However, risk analysis and scientific studies indicate that the risk from indoor exposure to asbestos fibers (even in buildings rich in asbestos materials) is extremely low and is about one-tenth the risk from breathing asbestos fibers found in outdoor air from natural sources (wind and erosion).

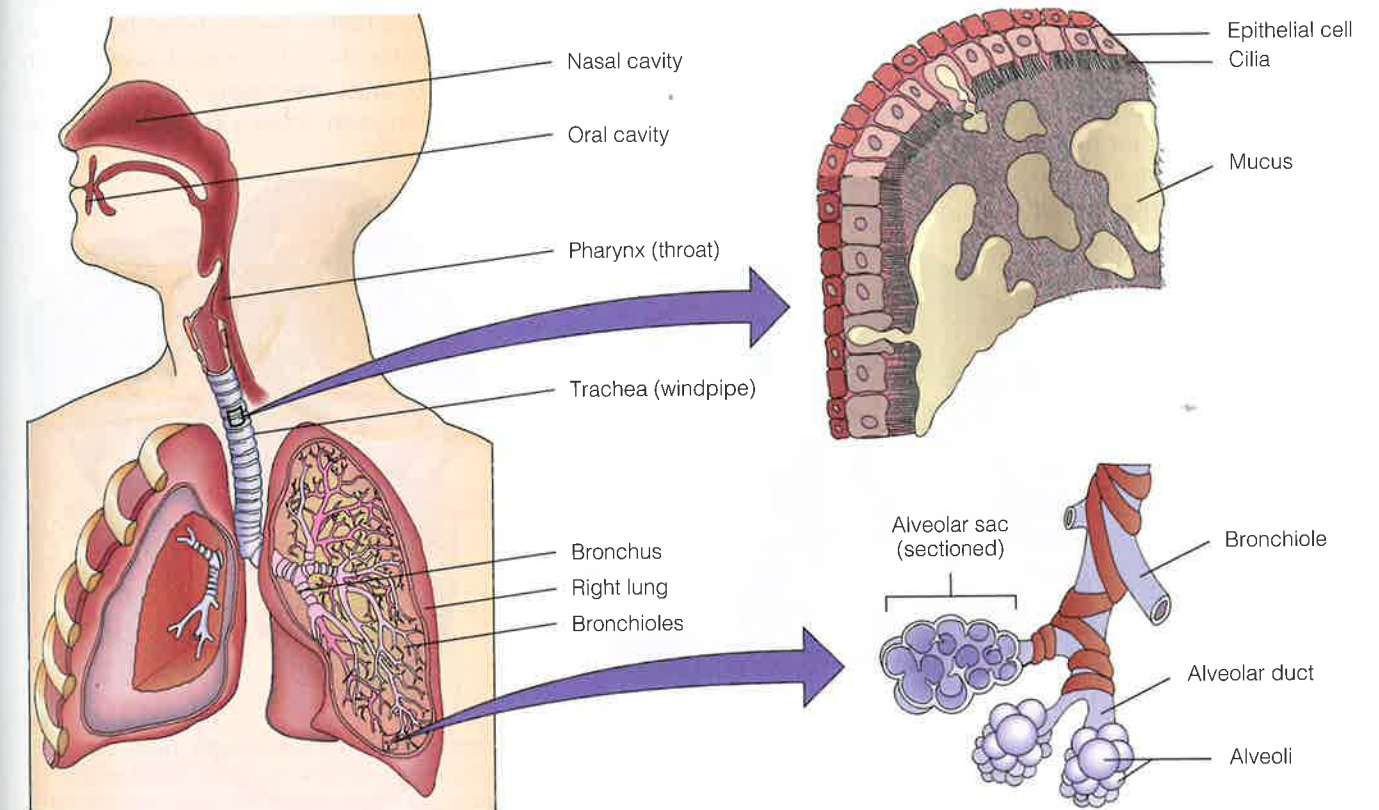
Critics argued that removing asbestos from buildings is a waste of money, with each life saved costing \$100–500 million. They called for sealing, wrapping, and other forms of containment instead of removal, except where asbestos has been damaged or disturbed. Indeed, improper or unnecessary removal can release more asbestos fibers than does sealing off asbestos that is not crumbling. In 1990, the EPA agreed with this and reversed its earlier policy. In 1998, chemists developed a foam that lets building owners treat asbestos-containing fireproofing material without removing it.

According to health experts, the major health risk from asbestos today is occurring among asbestos miners and workers in developing countries (especially Russia, China, Brazil, India, and Thailand), where the use of asbestos as an inexpensive building material is growing rapidly. Experts say that 90% of the worker deaths from asbestos exposure can be prevented by (1) using a good-fitting facemask, (2) wetting asbestos to control dust, and (3) changing clothes before and after handling asbestos.

## 17-6 EFFECTS OF AIR POLLUTION ON LIVING ORGANISMS AND MATERIALS

**How Does the Human Respiratory System Help Protect Us from Air Pollution?** Table 17-2 (p. 422) listed the major health effects from the six most common (criteria) outdoor air pollutants. Your respiratory system (Figure 17-18) has a number of mechanisms that help protect you from such air pollution. They include:

- Hairs in your nose that filter out large particles.
- Sticky mucus in the lining of your upper respiratory tract that captures smaller (but not the smallest) particles and dissolves some gaseous pollutants.



**Figure 17-18** Major components of the human respiratory system.



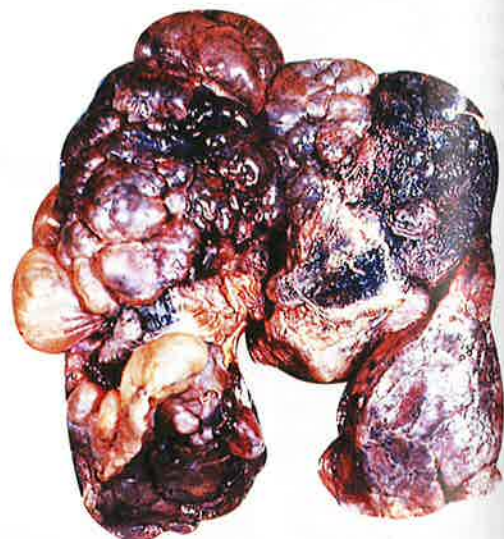
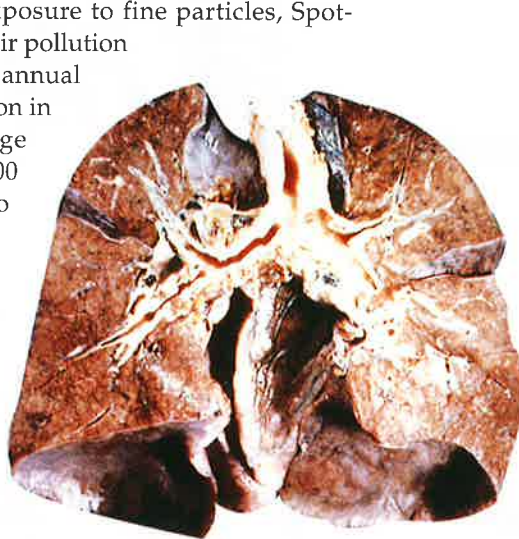
- Sneezing and coughing that expel contaminated air and mucus when pollutants irritate your respiratory system.
- Hundreds of thousands of tiny, mucus-coated hair-like structures called *cilia* that line your upper respiratory tract. They continually wave back and forth and transport mucus and the pollutants they trap to your throat (where they are swallowed or expelled).

Years of smoking and exposure to air pollutants can overload or break down these natural defenses. This can cause or contribute to respiratory diseases such as (1) *lung cancer*, (2) *asthma* (typically an allergic reaction causing sudden episodes of muscle spasms in the bronchial walls, resulting in acute shortness of breath), (3) *chronic bronchitis* (persistent inflammation and damage to the cells lining the bronchi and bronchioles, causing mucus buildup, painful coughing, and shortness of breath), and (4) *emphysema* (irreversible damage to air sacs or alveoli leading to abnormal dilation of air spaces, loss of lung elasticity, and acute shortness of breath (Figure 17-19). Older adults, infants, pregnant women, and people with heart disease, asthma, or other respiratory diseases are especially vulnerable to air pollution.

**How Many People Die Prematurely from Air Pollution?** It is difficult to estimate by risk analysis how many people die prematurely from respiratory or cardiac problems caused or aggravated by air pollution because people are exposed to so many different pollutants over their lifetimes.

In the United States, estimates of annual deaths related to outdoor air pollution range from 65,000 to 200,000 (most from exposure to fine particles, Spotlight, right). If indoor air pollution is included, estimated annual deaths from air pollution in the United States range from 150,000 to 350,000 people—equivalent to 1–2 fully loaded 400-passenger jumbo jets crashing *each day* with no survivors.

Millions more become ill and lose work time. A 2000 study by state and local air pollution officials estimated that each year more than 125,000 Americans (120,000 of them in urban areas) get cancer from breathing



**Figure 17-19** Normal human lungs (left) and the lungs of a person who died of emphysema (right). Prolonged smoking and exposure to air pollutants can cause emphysema in anyone, but about 2% of emphysema cases result from a defective gene that reduces the elasticity of the air sacs in the lungs. Anyone with this hereditary condition, for which testing is available, should not smoke and should not live or work in a highly polluted area. (O. Auerbach/Visuals Unlimited)

diesel fumes from buses, trucks, and other diesel engines. According to the EPA and the American Lung Association, air pollution in the United States costs at least \$150 billion annually in health care and lost work productivity, with \$100 billion of that caused by indoor air pollution.

According to a 1999 study by Australia's Commonwealth Science Council, worldwide at least 3 million people (most of them in Asia) die prematurely each year from the effects of air pollution—an average of 8,200 deaths per day. About 2.8 million of these deaths are from *indoor* air pollution, and 200,000 are from *outdoor* pollution (Figure 17-20).

Most people who live in large cities in developing countries breathe air that is the equivalent of smoking 2–3 packs of cigarettes a day. According to WHO estimates, up to 700,000 premature deaths per year worldwide could be prevented in developing countries if three pollutants—suspended particulate matter, carbon monoxide, and lead—were brought down to safer levels.

**How Are Plants and Aquatic Systems Damaged by Air Pollutants?** Figure 17-14 (p. 432) summarizes some of the direct and indirect effects of acidic deposition, ozone, and other air pollutants on trees, and the effects of acid deposition on trees and plants were discussed on p. 431.

The effects of exposure to a mix of air pollutants may not become visible for several decades, when large numbers of trees suddenly begin dying because of depletion of soil nutrients and increased susceptibility to pests, diseases, fungi, and drought (Connections, p. 431). This phenomenon, known as *Waldsterben* (for-



## Health Dangers from Fine Particles

Research indicates that invisible particles—especially *fine particles* with diameters less than 10 microns

(PM-10) and *ultrafine particles* with diameters less than 2.5 microns (PM-2.5)—pose a significant health hazard. Such particles are emitted by incinerators, motor vehicles, radial tires, wind erosion, wood-burning fireplaces, and power and industrial plants (Figure 17-7).

Such tiny particles (1) are not effectively captured by modern air-pollution control equipment, (2) are small enough to penetrate the respiratory system's natural defenses against air pollution (Figure 17-18), and (3) can bring with them droplets or other particles of toxic or cancer-causing pollutants that become attached to their surfaces.

Once they are lodged deep within the lungs, these fine particles can cause chronic irritation that

can (1) trigger asthma attacks, (2) aggravate other lung diseases, (3) cause lung cancer, and (4) interfere with the blood's ability to take in oxygen and release CO<sub>2</sub>. This strains the heart, increasing the risk of death from heart disease.

Several recent studies of air pollution in U.S. cities have indicated that fine and ultrafine particles prematurely kill 65,000–200,000 Americans each year. There is no known threshold level below which the harmful effects of fine particles disappear.

Exposure to particulate air pollution is much worse in most developing countries, where urban air quality has generally deteriorated. The World Bank estimates that if particulate levels were reduced globally to WHO guidelines, 300,000–700,000 premature deaths per year could be prevented.

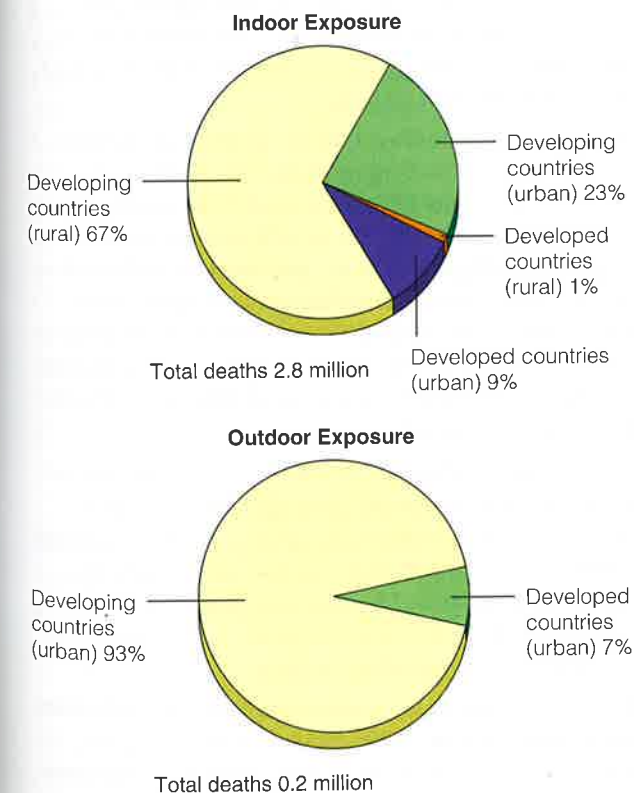
In 1997, the EPA announced stricter emission standards for ultrafine particles with diameters less than 2.5 microns (PM-2.5). The

EPA estimates the cost of implementing the standards at \$7 billion per year, with the resulting health and other benefits estimated at \$120 billion per year.

According to industry officials, the new standard is based on flimsy scientific evidence, and its implementation will cost \$200 billion per year. EPA officials say that their review of the scientific evidence—one of the most exhaustive ones ever undertaken by the agency—supports the need for the new standard for ultrafine particles. Furthermore, a 2000 study by the Health Effects Institute of 90 large American cities confirmed the link between fine and ultrafine particles and higher rates of death and disease.

### Critical Thinking

Are you for or against the stricter standard for emissions of ultrafine particles? Explain.



est death), has turned whole forests of spruce, fir, and beech into stump-studded meadows and mountainsides (see photo on p. 395). It is estimated that air pollution has been a key factor in reducing the overall productivity of European forests by about 16% and causing damage valued at roughly \$30 billion per year.

Forest diebacks have also occurred in the United States. The most seriously affected areas are high-elevation spruce trees that populate the ridges of the Appalachian Mountains from Maine to Georgia, including the Shenandoah and Great Smoky Mountain national parks.

Air pollution, mostly by ozone, also threatens some crops—especially corn, wheat, and soybeans, the three most important U.S. crops—and is reducing U.S. food production by 5–10%. In the United States, estimates of agricultural losses as a result of air pollution (mostly by ozone) range from \$2 to \$6 billion per year, with an estimated \$1 billion of damages in California alone. The effects of high acidity (low pH) on aquatic life were discussed on p. 430.

**Figure 17-20** Estimated premature deaths per year caused by indoor and outdoor air pollution in developing and developed countries. (Data from Australia's Commonwealth Science Council, 2000)



Table 17-3 Harmful Effects of Air Pollution on Materials

Material	Effects	Principal Air Pollutants
Stone and concrete	Surface erosion, discoloration, soiling	Sulfur dioxide, sulfuric acid, nitric acid, particulate matter
Metals	Corrosion, tarnishing, loss of strength	Sulfur dioxide, sulfuric acid, nitric acid, particulate matter, hydrogen sulfide
Ceramics and glass	Surface erosion	Hydrogen fluoride, particulate matter
Paints	Surface erosion, discoloration, soiling	Sulfur dioxide, hydrogen sulfide, ozone, particulate matter
Paper	Embrittlement, discoloration	Sulfur dioxide
Rubber	Cracking, loss of strength	Ozone
Leather	Surface deterioration, loss of strength	Sulfur dioxide
Textiles	Deterioration, fading, soiling	Sulfur dioxide, nitrogen dioxide, ozone, particulate matter

### What Are the Harmful Effects of Air Pollutants on Materials?

Each year, air pollutants cause billions of dollars in damage to various materials we use (Table 17-3). The fallout of soot and grit on buildings, cars, and clothing requires costly cleaning. Air pollutants break down exterior paint on cars and houses, and they deteriorate roofing materials. Irreplaceable marble statues, historic buildings, and stained glass windows around the world have been pitted, gouged, and discolored by air pollutants. The EPA estimates damage to buildings in the United States from acid deposition alone at \$5 billion per year.

## 17-7 SOLUTIONS: PREVENTING AND REDUCING AIR POLLUTION

**How Have Laws Been Used to Reduce Air Pollution in the United States?** The U.S. Congress passed Clean Air Acts in 1970, 1977, and 1990. These laws use a *command-and-control* approach in which the federal government establishes air pollution regulations that are enforced by each state and by major cities.

Congress directed the EPA to establish *national ambient air quality standards* (NAAQS) for six outdoor criteria pollutants (Table 17-2). The EPA regulates these chemicals by using *criteria* developed from risk assessment methods (Section 16-2, p. 398) to set maximum permissible levels in outdoor air.

One limit, called a *primary standard*, is set to protect human health, and another called a *secondary standard*, is intended to prevent environmental and property damage. Each standard specifies the maximum allowable level, averaged over a specific period, for a certain pollutant in outdoor (ambient) air. A geographic area that meets or does better than the primary standard for a particular pollutant is called an *attainment area*, and one that does not meet the primary standard is called a *nonattainment area*.

The EPA has also established national emission standards for more than 100 different toxic air pollutants that are known to cause or suspected of causing cancer or other adverse health effects.

Here is some *good news*. According to the EPA,

- Between 1970 and 1998, national total emissions of the six criteria pollutants declined 31%, while U.S. population increased 31%, gross domestic product increased 114%, and vehicle miles traveled rose 127%.
- Between 1978 and 1998, mean concentrations of the six criteria air pollutants in the troposphere decreased by (1) 97% for lead, (2) 60% for carbon monoxide, (3) 58% for sulfur dioxide, (4) 30% for ground-level ozone, (5) 25% for suspended particulate matter (10 micrometers or less in diameter), and (6) 2% for nitrogen dioxide.
- The mean estimated human health and environmental benefits from air pollution regulations between 1970 and 1990 amounted to \$6.8 trillion, compared to \$436 million (in 1990 dollars) spent to implement all federal, state, and local air pollution regulations. Thus, the net economic benefit of the Clean Air Act between 1970 and 1990 was \$6.4 trillion. During this 20-year period, the act prevented an estimated 1.6 million premature deaths and 300 million cases of respiratory disease.
- Between 1990 and 2010, the 1990 amendments to the Clean Air Act should provide four times more health and environmental benefits than the estimated compliance costs to industries and consumers. By 2010, the 1990 amendments should prevent 23,000 Americans from dying prematurely and avert 1,700,000 asthma attacks per year.
- A U.S. Court of Appeals decision in 2000 will allow implementation of a 1998 regulation requiring 32 older coal-fired plants in 10 states (mostly in the Ohio Valley and Midwest, Figure 17-10) to meet the same

air pollution emission standards as new coal-burning plants. According to the EPA, this will have the same effect as taking 26 million cars off the road and will bring cleaner, safer air to more than 138 million people living in the eastern half of the United States.

Here is some *bad news*.

- Between 1970 and 1998, emissions of nitrogen oxides (NO<sub>x</sub>) increased 11%.
- Despite continued improvements in air quality, in 1999 approximately 62 million people lived in 130 nonattainment areas with air that did not meet the primary standards for one or more of the six criteria pollutants.

### How Could U.S. Air Pollution Laws Be Improved?

The Clean Air Act of 1990 was an important step in the right direction, but many environmentalists point to the following deficiencies in this law:

- *Continuing to rely mostly on pollution cleanup rather than prevention.* In the United States, the air pollutant with the largest drop (97% between 1970 and 1998) in its atmospheric level was lead, which was virtually banned in gasoline.
- *Failing to increase fuel efficiency standards for cars and light trucks.* According to environmental scientists, this would reduce air pollution more quickly and effectively than any other method and would save consumers enormous amounts of money (p. 364).
- *Not adequately regulating emissions from inefficient, two-cycle gasoline engines used in devices such as lawnmowers, leaf blowers, chain saws, and personal marine engines used to power jet skis, outboard motors, and personal watercraft.* According to recent studies by the California Air Resources Board, (1) a 1-hour ride on a typical jet ski creates more air pollution than the average U.S. car does in a year, (2) operating a 100-horsepower marine engine for 7 hours emits more air pollutants than a new car driven 160,000 kilometers (100,000 miles), and (3) each year the fuel and oil spilled by the 14 million small marine engines in the United States is 15 times the amount spilled by the Exxon Valdez oil tanker (Case Study, p. 336).
- *Doing too little to reduce emissions of carbon dioxide and other greenhouse gases* (Section 18-5, p. 460).

Executives of companies affected by implementing such policies strongly oppose such changes in air pollution laws. They claim that implementing such changes would cost too much, harm economic growth, and cost jobs.

Proponents contend that history has shown that almost all industry estimates of implementing various air pollution control standards in the United States were many times the actual cost of implementation. In addition, implementing such standards has helped

increase economic growth and create jobs by stimulating companies to develop new technologies for reducing air pollution emissions. Many of these technologies are sold in the international marketplace.

**Should We Use the Marketplace to Reduce Pollution?** To help reduce SO<sub>2</sub> emissions, the Clean Air Act of 1990 allows an *emissions trading policy*, which enables the 110 most polluting power plants in 21 states (primarily in the Midwest and East, Figure 17-10) to buy and sell SO<sub>2</sub> pollution rights.

Each year a power plant is given a certain number of pollution credits or rights that allow it to emit a certain amount of SO<sub>2</sub>. A utility that emits less SO<sub>2</sub> than its limit receives more pollution credits. It can use these credits (1) to avoid reductions in SO<sub>2</sub> emissions from some of its other facilities, (2) bank them for future plant expansions, or (3) sell them to other utilities, private citizens, or environmental groups. Proponents of this system argue that it allows the marketplace to determine the cheapest, most efficient way to get the job done instead of having the government dictate how to control pollution.

Some environmentalists see this market approach as an improvement over the current regulatory approach, as long as it achieves net reduction in SO<sub>2</sub> pollution. This would be done by limiting the total number of credits and gradually lowering the annual number of credits, something that is not required by the 1990 amendments to the Clean Air Act.

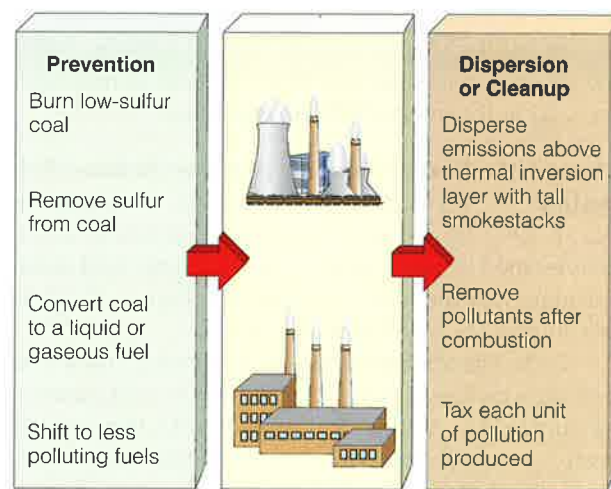
Some environmentalists contend that marketing pollution rights allows utilities with older, dirtier power plants to buy their way out and keep on emitting unacceptable levels of SO<sub>2</sub>. They also warn that this approach creates incentives to cheat. Air quality regulation is based largely on self-reporting of emissions, and pollution monitoring is incomplete and imprecise. Thus, sellers of permits will benefit by understating their reductions (to get more permits), and permit buyers will benefit by under-reporting emissions (to reduce their permit purchases).

Here is some *good news*. Between 1994 and 1997, the emission trading system helped reduce SO<sub>2</sub> emissions in the United States by 30%. The cost of doing this was less than one-tenth the cost projected by industry because this market-based system motivated companies to reduce emissions in more efficient ways.

In 1997, the EPA proposed a voluntary emissions trading program involving smog-forming nitrogen oxides (NO<sub>x</sub>) for 22 eastern states and the District of Columbia. Emissions trading may also be implemented for particulate emissions and volatile organic compounds.

**How Can We Reduce Outdoor Air Pollution?** Figure 17-21 summarizes ways to reduce emissions of sulfur oxides, nitrogen oxides, and particulate matter from stationary sources (such as electric power plants and industrial plants that burn coal). Until recently, emphasis has been on dispersing and diluting the pollutants



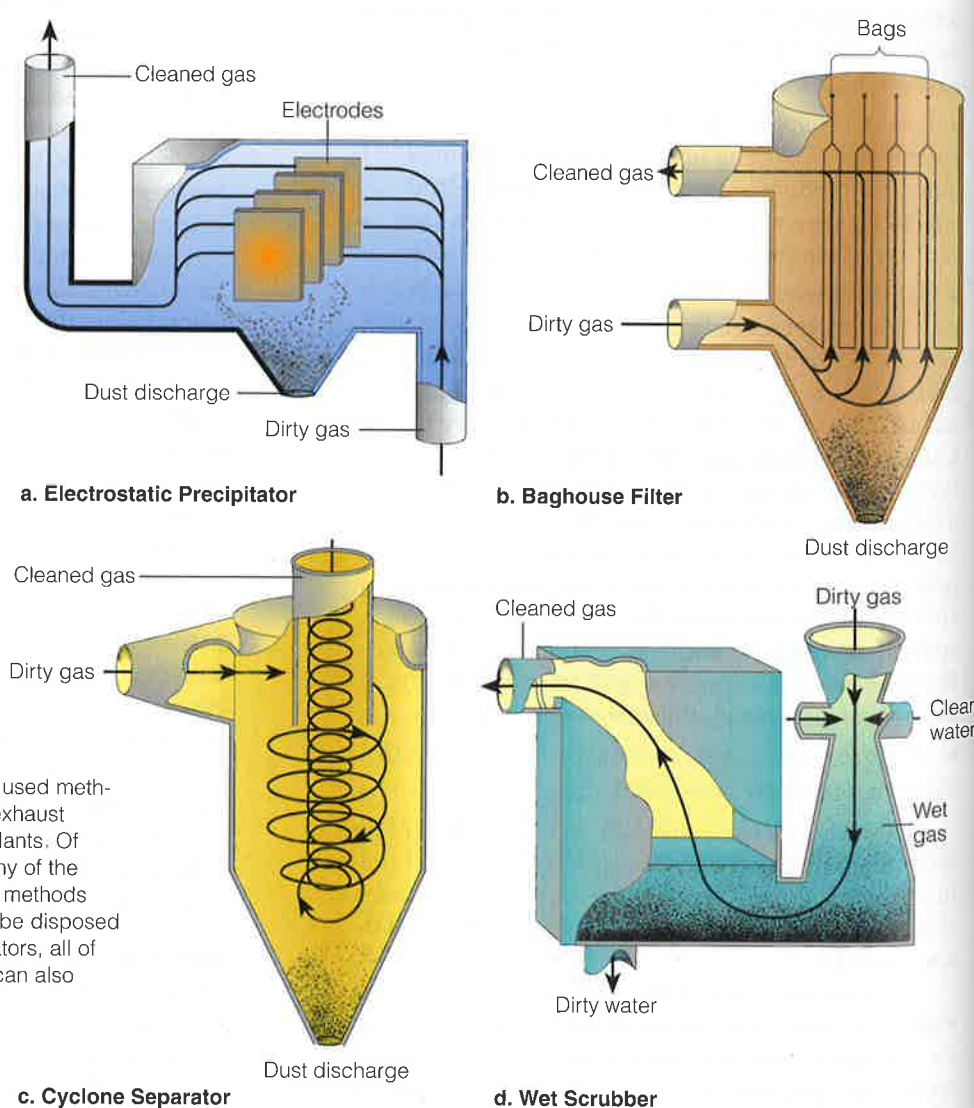


**Figure 17-21** Solutions: methods for reducing emissions of sulfur oxides, nitrogen oxides, and particulate matter from stationary sources such as coal-burning electric power plants and industrial plants.

by using tall smokestacks or adding equipment that removes some of the particulate pollutants after they are produced (Figure 17-22). However, under the sulfur reduction requirements of the 1990 amendments to the Clean Air Act, more utilities are switching to low-sulfur coal to reduce  $\text{SO}_2$  emissions. Environmentalists call for taxes on air pollutant emissions and greater emphasis on prevention.

Figure 17-23 lists ways to reduce emissions from motor vehicles, the primary culprits in producing photochemical smog. Use of alternative vehicle fuels to reduce air pollution is evaluated in Table 15-1, p. 385.

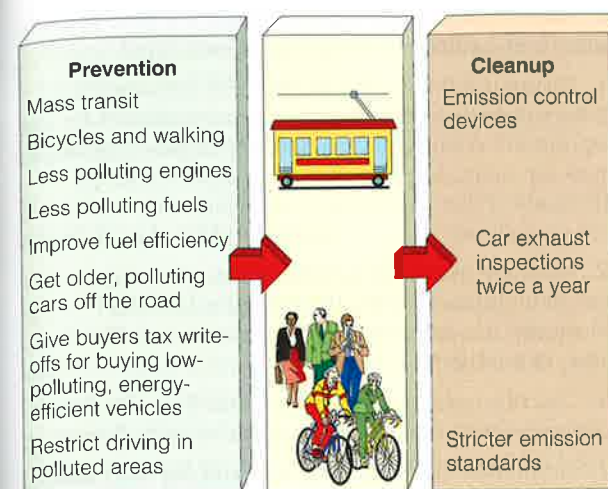
An important way to make significant reductions in air pol-



**Figure 17-22** Solutions: four commonly used methods for removing particulates from the exhaust gases of electric power and industrial plants. Of these, only baghouse filters remove many of the more hazardous fine particles. All these methods produce hazardous materials that must be disposed of safely, and except for cyclone separators, all of them are expensive. The wet scrubber can also reduce sulfur dioxide emissions.

lution is to get older, high-polluting vehicles off the road. According to EPA estimates, 10% of the vehicles on the road in the United States emit 50–70% of the pollutants. A problem is that many old cars are owned by people who cannot afford to buy a newer car. One suggestion would be to pay people to take their old cars off the road, which would result in huge savings in health and air-pollution control costs.

California's South Coast Air Quality Management District Council developed a drastic and controversial program to produce an 80% reduction in ozone, photochemical smog, and other major air pollutants in the Los Angeles area by 2009. This plan would (1) sharply reduce use of gasoline-burning engines over two decades by converting cars, trucks, buses, chain saws, outboard motors, and lawnmowers to run on electricity or alternative fuels, (2) substantially raise parking fees and assess high fees for families owning more than one car, (3) require gas stations to use a hydrocarbon vapor recovery system on gas pumps and to sell alternative



**Figure 17-23** Solutions: methods for reducing emissions from motor vehicles.

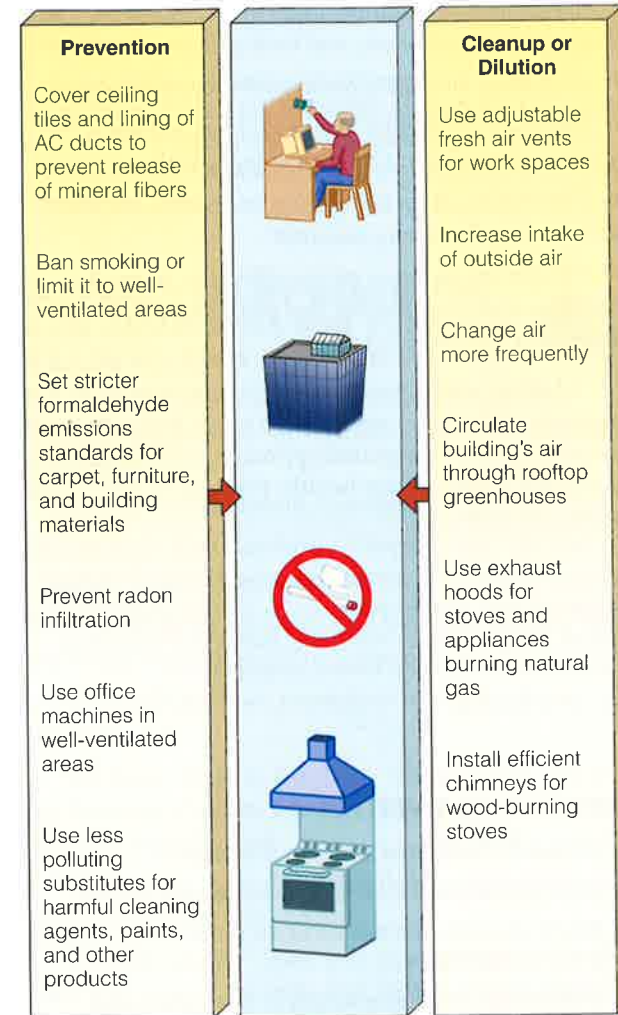
fuels (Table 15-1, p. 385), (4) strictly control or relocate industrial plants and businesses that release large quantities of hydrocarbons and other pollutants, and (5) find substitutes for or ban consumer products that release hydrocarbons, including aerosol propellants, paints, household cleaners, and barbecue starter fluids.

Here is some *good news*. Since the 1960s, Tokyo, Japan (with a current population of about 28 million), has implemented a strict air-pollution control program that has sharply reduced levels of sulfur dioxide, carbon monoxide, and ozone. During the past 30 years outdoor air quality in most western European cities has also improved. The *bad news* is that outdoor air quality has remained about the same or has gotten worse in most rapidly growing urban areas in developing countries.

**How Can We Reduce Indoor Air Pollution?** In the United States indoor air pollution poses a much greater health risk for many people than outdoor air pollution. Yet the EPA spends about \$500 million per year fighting outdoor air pollution and only about \$13 million a year on indoor air pollution.

To reduce indoor air pollution, it is not necessary to impose indoor air quality standards and monitor the more than 100 million homes and buildings in the United States. Instead, air pollution experts suggest that indoor air pollution can be reduced by several means (Figure 17-24). Another possibility for cleaner indoor air in high-rise buildings is rooftop greenhouses through which building air can be circulated. Some actions you can take to reduce your exposure to indoor air pollutants are listed in Appendix 6.

In developing countries, indoor air pollution from open fires and leaky and inefficient stoves that burn wood, charcoal, or coal (and the resulting high levels of respiratory illnesses) could be reduced if governments



**Figure 17-24** Solutions: ways to prevent and reduce indoor air pollution.

(1) gave people simple stoves that burn biofuels more efficiently (which would also reduce deforestation) and that are vented outside or (2) provided them with simple solar cookers (Figure 15-21d, p. 374).

**How Can We Protect the Atmosphere? An Integrated Approach** Environmentalists believe that protecting the atmosphere, and thus the health of people and many other organisms, will take a global approach that integrates many different strategies. Suggestions for doing this over the next 40–50 years include the following:

- Putting more emphasis on pollution prevention
- Improving energy efficiency
- Reducing use of fossil fuels (especially coal and oil)
- Increasing use of renewable energy
- Slowing population growth



- Integrating air pollution, water pollution, energy, land-use, population, economic, and trade policies
- Regulating air quality for an entire region or airshed
- Taxing the production of air pollutants and using the revenue to reduce taxes on income and wealth
- Distributing cheap and efficient cookstoves and solar cookstoves in developing countries
- Transferring the latest energy-efficiency, renewable-energy, pollution prevention, and pollution control technologies to developing countries

Making such changes will be controversial and expensive. However, proponents argue that not implementing such an integrated approach will cost far more in money, poor human health, premature death, and ecological damage.

*Turning the corner on air pollution requires moving beyond patchwork, end-of-pipe approaches to confront pollution at its sources. This will mean reorienting energy, transportation, and industrial structures toward prevention.*

HILARY F. FRENCH

## REVIEW QUESTIONS

1. Define the boldfaced terms in this chapter.
2. How can lichens be used to detect air pollutants?
3. Briefly describe the history of air pollution in Europe and the United States.
4. Distinguish between *atmosphere*, *troposphere*, and *stratosphere*. What key role does the stratosphere play in maintaining life on the earth?
5. Distinguish between the *greenhouse effect* and the *ozone shield* and explain the importance of these natural processes in sustaining life on the earth.
6. Explain how human activities are disrupting the carbon, nitrogen, and sulfur biogeochemical cycles.
7. Distinguish between *air pollution*, *primary air pollutants*, and *secondary air pollutants*. List the major classes of pollutants found in outdoor air. Distinguish between *stationary* and *mobile* sources of pollution for outdoor air. What are the two major sources of indoor air pollution?
8. List the six *criteria* air pollutants regulated in the United States (and in most developed countries). For each of these pollutants, summarize its major human sources and health effects.
9. What is *photochemical smog*, and how does it form? What is *industrial smog*, and how does it form?
10. List major factors that can (a) reduce air pollution and (b) increase air pollution. What is a *temperature inversion*, and what are its harmful effects? Distinguish between a *subsidence thermal inversion* and a *radiation tem-*

*perature inversion*. What types of places are most likely to suffer from prolonged inversions of each type?

11. Distinguish between *acid deposition*, *wet deposition*, and *dry deposition*. What areas tend to be affected by acid deposition? What is a *buffer*, and what types of geologic areas can neutralize or buffer some inputs of acidic chemicals? What two types of areas are most sensitive to acid deposition?
12. What are the major harmful effects of acid deposition on (a) human health, (b) materials, (c) soils, (d) aquatic life, (e) trees and other plants, and (f) some forms of wildlife?
13. Describe hidden synergistic interactions that can accelerate forest damage and decline by air pollution.
14. Summarize the major *good news* and *bad news* about acid deposition in the United States.
15. List seven ways to prevent acid deposition. What are the advantages and disadvantages of liming acidified lakes to reduce the effects of acid deposition?
16. How serious is indoor air pollution, and what are some of its sources? What is the *sick-building syndrome*? According to the EPA, what are the three most dangerous indoor air pollutants in the United States? What is the most dangerous indoor air pollutant in most developing countries?
17. Summarize the problem of indoor pollution from (a) formaldehyde, (b) radioactive radon gas, and (c) asbestos fibers.
18. List four defenses your body has against air pollution. What are the major harmful health effects of (a) carbon monoxide, (b) suspended particulate matter, (c) sulfur dioxide, (d) nitrogen oxides, and (e) ozone (See Table 17-2, p. 422)? Describe the health dangers from inhaling fine particles.
19. About how many people die prematurely each year from exposure to air pollutants in (a) the United States and (b) the world? What percentage of these deaths occurs in developing countries? What percentage of these deaths is the result of indoor air pollution?
20. What is the Clean Air Act, and how has it helped reduce outdoor air pollution in the United States? Distinguish between *national ambient air quality standards*, *primary standards*, and *secondary standards*. Distinguish between *attainment* and *nonattainment areas*.
21. Summarize the major *good news* and *bad news* about the effectiveness of the Clean Air Act in reducing outdoor air pollution in the United States. According to environmentalists, what are four weaknesses of the current Clean Air Act in the United States?
22. What is an *emission trading policy*, and what are the pros and cons of using this approach to help reduce air pollution?
23. List the major prevention and cleanup methods for dealing with air pollution from (a) emissions of sulfur oxides, nitrogen oxides, and particulate matter from sta-

tionary sources, (b) automobile emissions, (c) indoor air pollution in developed countries, and (d) indoor air pollution in developing countries.

24. What are ten components of an integrated approach for dealing with air pollution?

## CRITICAL THINKING

1. Evaluate the pros and cons of the following statement: "Because we have not proven absolutely that anyone has died or suffered serious disease from nitrogen oxides, current federal emission standards for this pollutant should be relaxed."
2. Identify climate and topographic factors in your local community that (a) intensify air pollution and (b) help reduce air pollution.
3. Should all tall smokestacks be banned? Explain.
4. Explain how sulfur in coal can contribute to the acidity of rainwater.
5. Suppose you become trapped in your car during a snowstorm and you have your engine and heater running to keep warm. Explain why you should roll down one of your windows just a little.
6. Why are most severe air pollution episodes associated with subsidence temperature inversions rather than radiation temperature inversions?
7. Evaluate your exposure to some or all of the indoor air pollutants in Figure 17-16 in your school, workplace, and home. Come up with a plan for reducing your exposure to these pollutants.
8. Should annual government-held auctions of marketable trading permits be used as a primary way of controlling and reducing air pollution? Explain. What conditions, if any, would you put on this approach?
9. Do you agree or disagree with the possible weaknesses of the U.S. Clean Air Act listed on p. 441? Defend each of your choices. Can you identify other weaknesses?

## PROJECTS

1. Have buildings at your school been tested for radon? If so, what were the results? What has been done about areas with unacceptable levels? If this testing has not been done, talk with school officials about having it done.
2. Write 1- to 2-page scenarios speculating about what types of species would survive and evolve if the concentration of oxygen in the earth's atmosphere (a) increased to 30% and (b) decreased to 15%.
3. Use the library or the internet to find bibliographic information about Michael J. Cohen and Hilary French,

whose quotes appear at the beginning and end of this chapter.

4. Make a concept map of this chapter's major ideas, using the section heads and subheads and the key terms (in boldface). Look at the inside back cover and on the website for this book for information about making concept maps.

## INTERNET STUDY RESOURCES AND RESOURCES FOR FURTHER READING AND RESEARCH



The website for this book contains helpful study aids and many ideas for further reading and research. Log on to:

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and click on the Chapter-by-Chapter area. Choose Chapter 17 and select a resource:

- "Flash Cards" allows you to test your mastery of the Terms and Concepts to Remember for this chapter.
- "Tutorial Quizzes" provides a multiple-choice practice quiz.
- "Student Guide to InfoTrac" will lead you to Critical Thinking Projects that use InfoTrac College Edition as a research tool.
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- "Hypercontents" takes you to an extensive list of sites with news, research, and images related to individual sections of the chapter.

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Dale, J. 2000. On the road to cleaner air. *State Legislatures* vol. 26, no. 3, pp. 12-17. (subject guide: air pollution, management)

Jaret, P. 2000. Experts are turning up some surprising sources of indoor air pollution. *National Wildlife* Feb-March 2000. (subject guide: indoor air quality)



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